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ENERGY OF OUR RESOURCES · THE POWER OF OUR IDEAS

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APRIL 24 - 26, 1989

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OTTAWA, ONTARIO

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DEDICATED
TO
THE MEMORY OF
R. DOUGLAS HAYES
1951 - 1989

These proceedings from the Seventh Canadian Bioenergy R&D Seminar are dedicated to the memory of R. Douglas Hayes, who passed away July 1, 1989. Since 1983, Doug managed the Bioenergy Development program of Energy, Mines and Resources Canada. He approached his work with the same determination, commitment and passion that he approached life. Doug had a sense of humour, a sense of caring and he found enjoyment in getting to know people - a quality which made him a valued coworker and friend. The bioenergy community will miss his expertise and knowledge. We will all miss him as a friend.

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INTRODUCTORY ADDRESS

Bruce Howe, Deputy Minister

Energy, Mines and Resources
Ottawa, Canada

Good morning, ladies and gentlemen, and welcome to the Seventh Canadian Bioenergy R&D Seminar.

This biennial event has become recognized as the major Canadian forum for bringing together those with an interest in bioenergy research and development. It gives me considerable pleasure to welcome you to this event, especially since it provides an opportunity to display the results of much of the innovative and promising research in the bioenergy field supported by my Department and by other agencies of the federal government.

These seminars have now been taking place for 10 years, originally under the auspices of the National Research Council and, more recently, with support from my Department. During this period, the contribution of bioenergy to Canadian primary energy requirements has risen from under 3% to a current level of approximately 7%. This is not an insignificant figure and is comprised of energy generated from a wide range of materials - including wood or agricultural waste, spent pulping liquor, and municipal solid waste - and with use in a variety of market sectors, including residences, institutions, and commercial and industrial buildings for both space and process heat or for electrical generation.

This increased bioenergy contribution has been accompanied by advances in biomass combustion technology and the development of significant bioenergy equipment design and manufacturing capability in Canada. Particularly impressive are the steps that some industries, such as the pulp and paper industry, have taken to recover energy from the wastes they generate. Some of the research sponsored by the federal government has done great service in improving the efficiency and controlling the emissions from these facilities, with yet more that can be done. Other advances in the areas of improved forest silviculture, intensive production of biomass, thermochemical conversion of biomass and wastes to a variety of energy-related products, biotechnology breakthroughs in the conversion of wood to fuel ethanol, oil from sewage sludge, and energy from municipal wastes are all testimony to the international acclaim of which Canadian bioenergy researchers can be proud.

Not only has the contribution of bioenergy to our energy requirements increased markedly during the last decade but there have also been other changes. Now, greater awareness of the need for respect for our environment is becoming a key issue for both public and governments. In the recent past our attention has been increasingly drawn to environmental problems of a magnitude or nature which are completely new to us. Historically, our concerns for the environment have been directed towards comparatively restricted, or site specific, impacts and the various levels of government have developed appropriate controls or remedial actions. Now we are seeing a number of problems which are of more global concern, where the activities of one nation or country can severely affect not only their own environment but also the environment of others. These problems, such as the global warming attributed to an increase in greenhouse gases, deterioration in the ozone layer, and the acid rain which is adversely affecting our lakes and forests, need new solutions.

We believe that we have already made an important step in starting on the road to the development of these solutions by becoming involved in international discussions. These have lead to the understanding that there is a global need to reduce emissions, such as CO_2, fluorocarbons and methane, and NO_x from automobile emissions. The next step is to develop strategies as how best to achieve these reductions, both nationally and internationally.

Energy use patterns have been identified as being a major contributor to these global problems; our current major reliance on fossil

fuels is considered a major threat to our global environment. At current consumption levels, nearly 5 billion tons of CO_2 are dumped into the atmosphere every year; 60% of this comes from burning fossil fuels. The decomposition of municipal waste in landfill site contributes significant quantities of methane, each molecule of methane being 20 times more active than CO_2 as a greenhouse gas.

Bioenergy, together with other renewable energy sources, can play an important role in helping to ensure a more environmentally appropriate energy mix for Canada and the world.

Currently, however, many of the uses of wood or waste for energy are not without their impacts on the environment. Depending upon the type of combustion process, industrial scale combustion can produce high levels of particulates or other products of incomplete combustion. The new generation of residential woodburning appliances, with their capability for highly controlled air access can, as a result of improper operation, release large quantities of unburnt products with concomitant concerns for health and safety.

With proper biomass-fuel preparation, advanced combustion technology and correctly operated facilities, combustion products arising from current-uses of biomass can be greatly decreased. We are also becoming increasingly aware that any energy-use of wood that is not accompanied by reforestation can add to atmospheric levels of CO_2.

Other technologies for bioenergy production and use are being developed which we predict will produce even fewer undesirable by-products.

One of our major ongoing thrusts is research and development in order to ready those technologies for the next round of market opportunities which will continue to ensure a future mix of environmentally appropriate energy sources. A number of technologies using biomass (such as liquefaction and some types of gasification, and the production of ethanol from cellulose) do not currently appear economically attractive. However, their economic attractiveness could improve markedly if competing technologies (including wood combustion or even fossil-derived energy sources) are subjected to increased emissions control and associated costs.

Additionally, one of western society's greatest contributions of air pollutants and carbon loading of the atmosphere is the transportation sector. Yet, unlike other sectors of our economy, there has been only minor penetration of alternative fuels into this market. Besides biomass-derived alcohol fuels and gasoline, there will be many other competitive alternative fuel and vehicle options seeking to capture a share of petroleum's current hold on the market. To be one of the successful contenders, bioenergy will have to prove its value to society in terms of environmental attractiveness, long-term sustainability and, most importantly, cost relative to conventional and other fuel alternatives.

The challenge facing us now is to work together to develop and promote those technologies that are environmentally appropriate and economically competitive with other energy sources. With identification and development of winning technologies that use more appropriate energy sources more efficiently we can not only reduce our own very high per capita use of energy and associated environmental costs, but can show a leadership role to the rest of the world. Of equal importance, the world can be a market for those technologies that we develop.

It is against this backdrop that I welcome you to this seminar. I believe that the excellent record of achievements in R&D and bioenergy use will allow us to continue to meet the increasing demands of today's world for safer and more efficient energy use.

I wish you every success during this seminar and in your future endeavors.

REMARQUES PRELIMINAIRES DE BRUCE HOWE, SOUS-MINISTRE ENERGIE, MINES ET RESSOURCES CANADA

Bruce Howe

Energie, Mines et Ressources Canada

Bonjour, Mesdames et Messieurs. Soyez les bienvenus au Septième Séminaire Canadien de R&D en Bioénergie.

Cet événement biennal est maintenant reconnu comme étant la principale tribune canadienne pour tous ceux qui s'intéressent à la recherche-développement bioénergétique. Je suis très heureux de vous accueillir à cet événement, tout particulièrement parce qu'il constitue une occasion de faire connaître les résultats de nombreuses activités de recherche innovatrices et prometteuses exécutées dans le domaine de la bioénergie grâce à l'appui d'Energie, Mines et Ressources Canada et d'autres organismes du gouvernement canadien.

Ce séminaire, qui se répète maintenant depuis dix ans, fut d'abord tenu sous l'égide du Conseil national de recherches, puis avec l'appui du ministère de l'Energie, des Mines et des Ressources du Canada. Au cours de cette décennie, la contribution de la bioénergie à la satisfaction des besoins du Canada en énergie primaire est passée de moins de 3 p. 100 à quelque 7 p. 100. Loin d'être négligeable, ce chiffre représente de l'énergie produite à partir de nombreuses matières, notamment des déchets de bois, des résidus agricoles, de la liqueur noire et des ordures ménagères. Cette énergie trouve son utilité entre autres dans les secteurs de l'habitation et des établissements ainsi que dans les édifices commerciaux et industriels, soit pour chauffer les locaux et comme source de chaleur industrielle ou pour la production d'électricité.

Cette utilisation accrue de la bioénergie s'est accompagnée de progrès technologiques touchant la combustion de la biomasse et de l'éclosion d'une compétence notable en conception et en fabrication de matériel bioénergétique au Canada. Et des projets particulièrement impressionnants furent menés à bien. Ainsi, certaines industries, notamment celle des pâtes et papiers, ont pris des mesures pour récupérer de l'énergie des déchets qu'elles produisent. Bien qu'il y ait plus encore à réaliser dans cette voie, des travaux de recherche parrainés par le gouvernement du Canada ont contribué largement à réduire les émissions provenant de ces installations et à améliorer leur efficacité. De plus, des chercheurs canadiens du secteur de la bioénergie ont mérité une reconnaissance internationale dont ils peuvent être fiers et ce, grâce à d'autres progrès, cette fois-ci dans les domaines de la sylviculture améliorée, de la production intensive de biomasse et de la conversion thermochimique de biomasse et de déchets en divers produits liés à l'énergie, ainsi qu'à des percées biotechnologiques dans le cadre de la conversion de bois en combustible à base d'éthanol et de la production de pétrole à partir de boues d'épuration, et d'énergie à partir d'ordures ménagères.

Au cours de la décennie, nous avons été témoins de plusieurs changements, dont une utilisation sensiblement plus fréquente de la bioénergie pour combler nos besoins énergétiques. Et maintenant, une sensibilisation accrue à la nécessité de protéger notre environnement est en voie de devenir une question primordiale, tant pour le public que pour les gouvernements. Récemment, nous nous sommes de plus en plus intéressés à des problèmes environnementaux d'une ampleur ou d'une nature qui nous étaient jusqu'ici complètement inconnues. Dans le passé, nos inquiétudes à l'égard de l'environnement concernaient des répercussions relativement limitées ou des répercussions sur des sites particuliers, et les différents ordres de gouvernement ont élaboré les méthodes de surveillance ou les mesures correctives qui s'imposaient. Nous faisons maintenant face à plusieurs problèmes qui touchent plus d'une région du globe, à des situations où un pays ou une nation peut, par ses activités, causer des dommages importants non seulement à son propre environnement, mais également à celui d'autres pays ou nations. Il nous faut trouver des solutions nouvelles à ces problèmes, qu'il

s'agisse du réchauffement mondial attribuable à une augmentation des gaz de serre, de la détérioration de la couche d'ozone ou des pluies acides responsables de la dégradation de nos lacs et de nos forêts.

Nous croyons qu'en nous engageant dans des discussions internationales, nous avons déjà franchi une étape importante afin de nous acheminer dans la voie menant à l'élaboration de ces solutions. Ce dialogue a mis en évidence la nécessité de réduire les émissions polluantes à l'échelle du globe, notamment le CO_2, les fluorocarbures, le méthane et le NO_x provenant des émanations des automobiles. Nous devons maintenant établir des stratégies qui nous permettront de réaliser ces réductions de la meilleure façon qui soit, tant sur la scène internationale qu'au Canada.

Il fut déterminé que divers modes d'utilisation de l'énergie étaient grandement responsables des problèmes environnementaux existant sur toute la planète; notre dépendance élevée à l'égard des combustibles fossiles est considérée comme un risque important pour l'environnement de notre planète. Les niveaux de consommation actuels sont tels que presque cinq milliards de tonnes de CO_2 sont rejetées dans l'atmosphère chaque année; 60 p. 100 de ces rejets résultent de la combustion de sources d'énergie fossiles. La décomposition des ordures ménagères dans les sites d'enfouissement produit beaucoup de méthane. Or, chaque molécule de méthane est vingt fois plus active que le CO_2 en tant que gaz de serre.

La biomnergie ainsi que d'autres sources d'énergie renouvelables peuvent contribuer largement à la constitution d'une gamme de sources d'énergie davantage acceptable du point de vue environnemental et ce, au Canada et partout ailleurs dans le monde.

Toutefois, à l'heure actuelle, de nombreux modes de production d'énergie à partir de bois ou de déchets ont des répercussions sur l'environnement. Selon le type de procédé utilisé, la combustion à l'échelle industrielle peut produire des niveaux élevés de particules ou d'autres produits de combustion incomplète. La nouvelle génération d'appareils de chauffage au bois pour les maisons est dotée de prises d'air à commandes très précises. En cas de mauvais fonctionnement, ces appareils peuvent libérer de grandes quantités de produits imbrûlés et s'avérer inquiétants du point de vue de la santé et de la sécurité.

Nous savons qu'une préparation adéquate du combustible biomassique, une technologie de combustion avancée et des installations exploitées comme il se doit permettent de réduire considérablement les produits de combustion résultant des usages courants de la biomasse. Et nous sommes de plus en plus conscients du fait que toute utilisation du bois à des fins énergétiques qui ne s'accompagne pas d'un reboisement peut augmenter les niveaux de CO_2 dans l'atmosphère.

D'autres techniques de production et d'utilisation de la biomnergie sont en voie de développement, et l'on prévoit qu'elles généreront encore moins de sous-produits nuisibles.

La recherche-développement représente l'un des domaines sur lesquels nous concentrons actuellement nos efforts en vue de rendre ces techniques prêtes à être commercialisées dès que se manifestera la prochaine occasion de profiter des possibilités offertes par le marché, laquelle continuera à assurer dans l'avenir le maintien d'un éventail de sources d'énergie compatible avec les objectifs environnementaux. A l'heure actuelle, plusieurs techniques comportant l'utilisation de la biomasse (comme la liquéfaction, certains types de gazéification et la production d'éthanol à partir de cellulose) ne semblent pas intéressantes du point de vue économique. Leur intérêt économique pourrait toutefois s'améliorer sensiblement si des techniques concurrentielles (notamment la combustion du bois, ou même des sources d'énergie dérivées de matières fossiles) étaient soumises à une réglementation accrue sur le plan des émissions et si elles devaient porter le fardeau des coûts connexes.

Dans les pays de l'ouest, le secteur des transports constitue l'une des principales sources de rejet de polluants dans l'air et d'accumulation de carbone dans l'atmosphère. Les carburants de remplacement ne se sont néanmoins gagné qu'une petite part du marché des transports, contrairement à ce qui s'est passé dans d'autres secteurs de notre économie. Le pétrole, qui domine actuellement le marché, devra soutenir la concurrence de l'essence, des carburants alcoolisés dérivés de la biomasse, de nombreux autres carburants de remplacement compétitifs et de plusieurs options pour les véhicules. Afin de se retrouver dans le cercle des vainqueurs, la biomnergie devra prouver qu'elle constitue une option viable à long terme et une solution intéressante sur le plan environnemental. Mais, plus important encore, le coût de la biomnergie devra être attirant par rapport aux carburants classiques et à d'autres carburants de remplacement.

Nous avons maintenant un défi à relever. Nous devons en effet unir nos efforts pour développer et promouvoir les techniques qui sont acceptables du point de vue environnemental et tout aussi rentables que les techniques propres à d'autres sources d'énergie. En identifiant et en élaborant des techniques qui exploitent plus efficacement des

sources d'énergie plus opportunes, nous pouvons non seulement réduire la très grande utilisation d'énergie par personne au Canada ainsi que ses répercussions environnementales, mais nous pouvons également nous affirmer en tant que chef de file sur la scène mondiale. Et qui plus est, le marché international peut s'avérer une source de débouchés pour les techniques que nous développons.

J'ai jugé bon de vous décrire cette réalité au moment de vous souhaiter la bienvenue à ce séminaire, car elle en constituera la toile de fond. Je crois que les très nombreuses réalisations dans les domaines de la recherche-développement et de l'utilisation de la bioénergie nous permettront de continuer à satisfaire une demande de la société actuelle, soit un usage plus sûr et plus efficace de l'énergie.

J'espère que ce séminaire sera pour vous des plus profitable et que tous vos projets seront couronnés de succès.

SUSTAINABLE DEVELOPMENT AND THE IMPLICATIONS ON ENERGY AND BIOENERGY FROM A GLOBAL PERSPECTIVE

Lutz Baehr, Director

Centre for Science and Technology
for Development, United Nations

I am very pleased and regard it as a special honour to give this luncheon address on "Sustainable Development and the Implications on Energy, in particular on Bioenergy, from a Global Perspective" at this Seventh Canadian Bioenergy R&D Seminar.

However, I have to admit that I am not a specialist or scientist in bioenergy, therefore, I shall not make the attempt to raise any scientific issues which are related to bioenergy and its application.

I would also understand if someone would raise the question on the qualifications of the United Nations Centre for Science and Technology to talk on these issues. Although I could comfortably lean back and leave the reply to the organizers of this seminar, I would like to make the humble remark that the United Nations, and the Centre which I represent, have very much to do with sustainable growth, energy, bioenergy and more so with the global perspectives of these issues.

The concept of sustainable development, which reflects on a more balanced and long-term development, on the idea of sustaining growth for all and for future generations, on growth in harmony with our environment, emerged from the Brundtland Commission in 1988. It is true that this concept is not totally new. Some of its elements were reflected almost twenty years ago in the so called "Pearson Report" which constituted the basis of the Second Development Strategy, namely the Development Strategy of the United Nations for the Seventies. This Pearson Report - and I think this seminar is a very good occasion to make reference to this very specific and important strategy - introduced, in my view, two basic strategic elements into the international discussions on development in the late sixties. It emphasized the social dimensions of economic growth, and secondly, focussed on the global and national interrelationship of development. The United Nations has always, and especially since then, provided this understanding of development. The United Nations system has, at a relatively early stage, been conscious of the relationship between socio-economic development and changes in the natural environment. In fact, it has succeeded to a large extent in mobilizing the international community to mitigate the adverse effects of our traditional understanding of economic growth on the environment.

What is new, and one of the underlying factors leading to the concept of sustainable development, was the inclusion of climate change and variability in the report of the Brundtland Commission "Our Common Future". This report, together with the Montreal Protocol on "The Depletion of the Ozone Layer", as well as the Toronto Conference on "The Changing Atmosphere-Implications for Global Security" in 1988 have created an increased awareness of the threat for humankind resulting from such human made changes of the global climate patterns as global warming, the greenhouse effect and the depletion of the ozone layer.

In light of these developments, the United Nations Centre for Science and Technology felt that it could not remain in silence, and that it had to respond to the challenges addressed to science and technology in initiating innovative approaches to mitigate the causes of climate change. It also had to react, because it became evident that the same science and technology, which is considered as a vehicle of economic growth and progress, can turn against humankind if it is not properly used. This applies in particular to energy technologies.

Together with a specialized scientific institute in the Federal Republic of Germany, the Centre organized the World Congress on

Climate and Development, which took place in Hamburg from 7 to 10 November 1988.

As with the Toronto Conference, the Hamburg Congress was seeking scientific classifications and options for further action arising out of the current national and international perceptions. However, the Hamburg Congress went beyond the Toronto Conference, because it gave room for the exchange of controversial viewpoints, namely of individuals and groups with different stakes in this discussion. These were policy makers, scientists, engineers, representatives of the energy sector, environmental groups and representatives of industrialized and developing countries. In spite of the diversity of views, the seriousness of the threat as expressed in previous conferences was confirmed. Also, very little differences existed in the findings that the chief atmospheric pollutants are carbon dioxide (CO_2), chlorofluorocarbons (CFC's), methane (CH_4), tropospheric ozone (O_3) and nitrous oxide (NO_x).

The sources of these emissions are clearly attributed to a number of human activities related to the inefficient use of fossil fuels, certain land use methods and certain industrial practices requiring synthetic chemicals used as coolants and solvents. Therefore the issue is not whether these pollutants contribute to the predicted climate change, but how effectively they can be controlled, or eliminated. Controversies remain with regard to the extent and speed of actions to be taken to control or eliminate these causes.

Controversies also arose between the representatives of industrialized and developing countries on the relative capability of individual polluting states to mobilize additional funds to effectively tackle the causes of atmospheric pollution. Although it was largely recognized by developing countries that international cooperation was imperative to reduce the extent of atmospheric pollution, it also became clear that it would be difficult to involve developing countries in joint programs since many of these countries are struggling for economic and financial survival. Some representatives of developing countries also indicated that they were not in a position to accept any additional financial burdens related to future problems resulting from atmospheric pollution which, in their perspective, are mainly caused by industrialized countries.

What appears even more dramatic is that the struggle for daily survival in many developing countries forces people to overexploit nature and there are also indications that the pressures of debt accelerate excessive exploitation of natural resources. This again adversely affect the global climate. Finally, although the proportion of developing countries world-wide energy production is presently not more than 20%, their fossil fuel consumption will increase drastically in the near future. For example, the energy generation of China and India, which comprise almost 40% of the world population, is mainly based on coal burning, because coal is available and relatively economic. In both countries the per capita energy consumption is still extremely low. Both countries are now undertaking enormous efforts to foster industrialization and because of this, energy rates increasing by 10 to 15 percent per annum are not unlikely.

To summarize some of the major results of the Congress in Hamburg, it can be stated that in the opinion of the more than 400 participants:

- drastic changes will be needed in industrial production methods, patterns of land use and energy use
- or modifications in life styles will be necessary to enforce conservation of energy. The nuclear option to reduce CO_2 pollution seems too distant
- matically, benign technologies and ecologically sound agricultural production methods should be vigorously promoted
- developing countries need to be assisted to allow them to be in a position to undertake their own autonomous analysis and assessment of the implications of global climate change.
- unlateral and multilateral programmes have to be designed to help facilitate the flow of environmentally sustainable technologies that could serve to reduce the emission of greenhouse gases;
- eduction of CO_2 emissions by 30% by the end of this century. (You might recall that the conference in Toronto had recommended a 20% reduction of CO_2 emissions by the year 2000.)

If in the present international discussion, a reassessment of the nuclear option is not seriously considered, then four major options remain to reduce CO_2 emissions:

1. increase in energy efficiency
2. conservation of energy
3. shifts from oil and coal towards natural gas
4. energy alternatives such as solar, biomass, tidal, wind and geothermal

It is evident that in the majority of developing countries, only the fourth option constitutes a realistic approach. In particular, solar and biomass energy seem to be a more suitable solution to their energy needs,

especially in rural areas, because they do not require connected systems.

On one hand, biomass based energy production is more economic than solar energy, on the other hand, it produces CO_2 emissions, although, and this is a crucial point, at a much lesser extent than fossil fuels.

As the international discussion on CO_2 reduction focusses on energy production related to industrial and domestic consumption, I would also like to make a brief reference to a comparative analysis of future transportation fuels, prepared by the University of California. This study examined the emission of greenhouse gases (CO_2, CFC's, O_3, N_2O, CH_4) from prominent highway energy options: petroleum, methanol, natural gas, electric vehicles, and hydrogen. The study was prepared against the background that transportation fuels in the United States account for about 27% of the total CO_2 emissions in the United States which contributes 1/4 of the total world production of CO_2. The study came to the conclusion that significant reductions in the emission of greenhouse gases can be attained only by greatly increasing vehicle efficiency and by using biofuels, electrolytic hydrogen, or non-fossil electricity as the fuel feedstock.

It recommends that fuels and technologies be priced at their social cost, i.e. full economic cost, in order to make alternative transportation energies more economically attractive. It also recommends financial support for R&D on suitable, clean, non-CO_2 producing technologies. It concludes that proper pricing of petroleum fuels will encourage efficiency improvements and reduced CO_2 emissions proportionally, and increase efficiencies of resource use. Proper pricing combined with increased R&D on solar energy production and hydrogen and electric vehicles will hasten the efficient adoption of sustainable, environmentally sound, non-CO_2 producing transportation options.

In order to discuss this and other issues related to transportation energies, the Centre is organizing, in close cooperation and with the support of the Government of Canada and the University of California, a workshop in Ottawa, 20 to 23 September 1989.

In concluding my presentation, I wish to point out that this announcement is another example that Canada plays an important role in the international discussion on energy and is implications on climate. However, as our limited experience with the Hamburg Congress on climate and development illustrates, the increased awareness of these issues have not yet led to decisive actions directed to sustainable development in the future. This, in my view, should not be seen as a discouraging factor. On the contrary, it underlines the need for seminars and conferences of this kind in order to prepare and initiate policy options before it is too late to stabilize the atmosphere pollution. I think we all agree that the concept of sustainable development still constitutes an intellectual challenge, and more so, a political challenge to implement it. But, I think there is no alternative to the concept of sustainable growth, therefore, we have to accept this challenge. Especially, if we agree that - as Lester Pearson stated 20 years ago - the responsibilities for development cannot be divided and these responsibilities should also comprise the world of future generations.

BIOENERGY OVERVIEW
7th CANADIAN BIOENERY R&D SEMINAR

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This is rather an auspicious time for bioenergy development in Canada. Indeed this year marks the tenth Anniversary of significant involvement by the Canadian government in bioenergy. Prior to this, the government was involved, in a very limited fashion, in supporting some ad hoc R&D work and some demonstrations as part of a series of measures introduced in response to the 1973 OPEC oil embargo. In 1977, the government of the day became even more serious about renewable energy with the establishement of a Renewable Energy Branch within EMR.

It was really only in mid 1978 that the government announced several programs that would have a profound effect on the development of bioenergy and it was only 1979 that these programs really got going and became operational. These programs included:

1. The Forest Industry Renewable Energy Program (FIRE) which provided financial incentives to the forest products industries to utilize their residues and wastes to displace fossil fuels.

2. The Canadian Renewable Energy Demonstration Program or CREDAs which provided funding assistance to demonstrate the technical and commercial viability of bioenergy technologies on a large scale.

3. The ENFOR or Energy From the Forest R&D program for the production and conversion of forest biomass.

In 1979, there was a further dramatic price rise in oil by OPEC which led directly to the introduction of the National Energy Program (NEP) in 1980. The NEP was an interventionist program aimed at the substitution of oil with other more abundant or renewable energy sources and at Canadianizing our fossil fuel industry. The NEP greatly expanded the effort in renewable energy. In terms of its impact on bioenergy, the NEP expanded the FIRE Program making all biomass sources eligible, not only forest biomass; this resulted in a considerable effort in the energy from municipal waste (EFW) area; and it saw the introduction of the Canada Oil Substitution Program (COSP) which provided financial incentives to the residential sector to convert from oil to other alternatives including wood. In addition, a lot more money was poured into energy R&D.

So on this tenth anniversary of federal involvement in bioenergy, it is appropriate to review Canadian bioenergy development. This is not intended to be a technical overview but rather, a review of Canadian bioenergy development against a background of changing policy including;

- energy policy
- fiscal policy
- S&T policy, and
- environmental issues

CHANGING ENERGY POLICY

Ten years ago, federal energy policy was, of necessity, based on crisis management. OPEC seemed to be able to raise oil prices at will. Oil prices were predicted to go from the $40/bbl range at the time to $90/bbl range by the 1990's. The National Energy Board reported that Canada had only 7 to 11 years of conventional oil reserves and that we were rapidly running out of natural gas.

Just over 10 years ago, approximately 55% of our total energy supply came from oil. Canada as well as other countries were facing an oil crisis in terms of supply and price. Two points worth noting are:

1) Oil prices began to ease at the end of 1985 and the bottom fell out in 1986 when prices dropped as low as $10 U.S./bbl. They have now stabilized in the $18 to $20 U.S./bbl range. The latest 1988 NEB projections estimate oil prices going to $30/bbl U.S. by the year 2000 in the high economic growth price scenario, in which by the way, it is expected that Canada will remain a net oil exporter. In the low economic growth senario, oil prices are projected to climb only to $20 U.S./bbl by the year 2000. Canada will become a net oil importer. Thus, oil prices are not projected to change much in the forseeable future.

2) The 1988 NEB report states that Canada has conventional oil reserves which will last for 11 to 12 years at current production rates, which is higher than its estimates of 10 years ago. The NEB also shows a huge natural gas surplus with supply lasting until well into the 21st century (i.e. about 40 years).

In summary, 10 years ago we were in an oil crisis situation in terms of supply and price, now supply and price of oil and other fossil fuels do not appear to present any problems for the mid term; public opinion polls show that energy is no longer a major issue as far as the general public is concerned which is contrary to the situation which existed 10 years ago. Energy is again taken for granted.

FISCAL POLICY

The current government has identified the national debt as a major problem. The cummulative national debt is over $300 billion and is increasing at the rate of about $30 billion per year. This $30 billion is approximately what it is costing the government in interest payments alone to service this debt. This is more than twice as much as it costs the government for economic and regional development, and more than twice what it costs for all benefits to the elderly. Without these interest payments Canada would have a balanced budget. The current government is committed to reducing this deficit and has been successful in slowing the rate of its increase over the past few years.

As a result, there has been a tremendous shift in fiscal policy away from huge spending on discretionary incentive programs. The key elements of current fiscal policy are restraint and non-intervention, that is the evolution of a more market driven economy.

The impacts of this fiscal policy on Canadian energy policy has been a dramatic reduction in spending on energy R&D which led to the shutdown of the renewable energy R&D program at the NRC in 1984; the dismantling of the National Energy Program beginning in 1985 which included the cancellation of COSP and the Canadian Home Insulation Program (CHIP).

Other conservation and renewable energy programs such as FIRE and the demonstration program were brought together under the National Conservation and Alternative Energy Program or NCAEI. NCAEI was basically designed to wind down the remaining sunsetted NEP and pre NEP conservation and alternate energy programs. NCAEI had no new initiatives.

In August 1988, Cabinet approved a new initiative to replace NCAEI which ended March 31, 1988. This new initiative is called the Energy Efficiency and Diversity Initiative (EED). The stated mission of EED is to enhance Canada's industrial competetiveness, energy security, and physical environment by the promotion of Efficiency in energy use and Diversity of energy sources and technology.

Cabinet's decision was a good news/bad news situation. The good news was that the federal mandate for continued work in this area was confirmed, and the funding was approved to 1992-93. The bad news was that no new program funds were approved.

What this means in actual program budgets for EED over the 5 year period is shown in Figure 1. Of the total of $74.2M allocated last year, (EED included the 1988-89 fiscal year) $18.1M was for R&D. This R&D money is allocated through the Federal Panel on Energy R&D which coordinates all federal spending on energy R&D. This $18.1M remains constant over 5 years; it includes R&D activities in conservation, transportation energy, solar, wind, small hydro, as well as bioenergy. The $4.0M in non-panel R&D funds, were additional funds allocated to renewable energy R&D under NCAEI back in 1985 to help cushion the drop in R&D funding which occurred when NCR dropped its program in this area. This non-panel R&D funding drops to $2M this year, although this is yet to be confirmed, and then disappears. The remainder of the EED budget includes the A-base or watching brief activities as well as the wind-down of the NCAEI programs, that is, paying the bills on projects previously approved under NCAEI. These funds disappear in the 1989/90 fiscal year leaving R&D and watching brief activities in 1990/91. (Mr. Wilson's budget April budget further reduced the overall EED budget by $8M in 1989/90 and $10M in 1990/91).

The EED R&D budget is shown in Figure 2.

Figure 3 illustrates how federal government funding for bioenergy has fared over the past 10 years or so. About 10 years ago, federal funding was just under $5M. With the NEP, funding increased dramatically, peaking at just under $20M in 1984. Funding then plummetted with NRC's withdrawal and subsequent cutbacks to the panel funding to the point of almost where it was 10 years ago (actually worse since it does not include inflation). Budget increases by a factor of 4 followed by decreases by a factor of 4 over a 10 year period have presented some difficult problems in trying to manage this program.

The bioenergy R&D budget profile mirrors that of the total federal energy R&D budget coordinated by the Panel with total funding increasing from about $10M in 1976-77 to $170M in 1984-85 and back to about $90M in 1989-90 (Figure 4).

EED - THE NEW APPROACH

EED is very much a non-interventionist, or market driven initiative. In other words the Department will be relying on the market to take the lead and we shall play a facilitative or support role. The focus will be on the business sector and hopefully to an increasing extent on the environment and the role that EED technologies can play in ameliorating our environmental problems.

EED will attempt to get more bang for the buck by being more targetted; obtaining a greater leaverage of our dollars from our clients, especially the private sector; increasing awareness of opportunities by doing a better selling job of our services; and expertise and, stimulating new investments in this area.

EED will build on its strengths and the successes which have been achieved over the past 10 years and only viable new options will be pursued. Finally, under EED we shall attempt to simplify our dealings with our client groups and the provinces by making them less bureaucratic.

FEDERAL SCIENCE POLICY

The non-interventionist, market-driven philosophy is also directing federal R&D programs. In March of 1987, the Ministry of State for Science and Technology (now known as the Department of Industry, Science and Technology, DIST) issued a framework for various departments for the management of federally supported Science and Technology activities. This framework enunciated three basic principles:

1. S&T work should be done in the private sector or universities as opposed to government labs wherever feasible.

2. Federal funds must be leaveraged.

3. Federal S&T activities should be sensitive to;
   - economic and regional development
   - the mission or mandate of the department
   - the advancement of scientific knowledge.

These S&T principles are consistent with government fiscal policy of taking a non-interventionist approach.

ENVIRONMENTAL ISSUES

It is impossible to pick up a newspaper or magazine these days without reading an article about a current or impending environmental disaster. It is a key factor in the minds of the public. In fact it is the most important issue in the minds of the public according to public opinion polls. It has therefore become an important factor in the minds of our politicians. There is real concern about toxic wastes, acid rain, depletion of the ozone layer, CO_2 build-up and the greenhouse effect.

It is interesting to note that these concerns are focussed on health and economic risks where as in the past concerns were more about aesthetic values. It is one thing to say that acid rain is killing the lakes but another to say that it is affecting the drinking water through leachates and it is destroying forests and therefore the future viability of the forest products industry. There is increasing recognition by governments that the environment must be considered of equal importance in planning economic and energy related activities. The theme of sustainable development has captured world wide attention in the Bruntland Commission Report, Our Common Future. It has been re-emphasised in the Report of the National Task Force on the Environment and Economy, submitted to the Canadian Council of Resource and Environment Ministers and in the report on Energy and Canadians into the 21st Century - which was a report on the Energy Options Process issued last year.

CHANGING GOVERNMENT POLICIES

The new realities being brought about by the changing energy policy, fiscal policy, S&T policy, and emerging concerns over the envrionment are forcing a re-evaluation of our bioenergy program direction, its priorities and its management. Some of the current issues which have been brought about by these changing policies are:

1) Working more closely with industry.
2) Working with large versus small companies.
3) Supporting R&D for export versus domestic markets.
4) Short versus long term R&D activities.
5) Leverage and ownership of intellectual property.
6) Proactive versus reactive R&D.
7) Energy prices and environmental concerns.

WORKING WITH INDUSTRY

Working more closely with industry presents a difficult problem for the Bioenergy Program because a clearly identifiable bioenergy industry does not exist in the same sense that there is an oil industry, a natural gas industry or a coal industry. An association of a few major companies in each of the latter will capture the main interests of the industry.

For the most part the "bioenergy industry" is a disparate group of companies whose main interests are in other areas such as in pulp and paper or other forest products, agriculture, engineering, fabrication of wood stoves, biotechnology or whatever. All have a wide range of very different interests and it is difficult to identify a common need. Furthermore, there is no unified voice speaking on behalf of the industry in dealing with the government. Somehow we need to bring these interests together.

LARGE VERSUS SMALL COMPANIES

Large companies in general have more resources available to them in terms of personnel, financing, marketing and a broader technology base. These companies therefore have a better chance of succeeding and do not need EMR as much. On the other hand, small companies tend to have more new ideas, are more flexible and adaptable but need more support such as financial, technical and marketing. There is a need to work with a balance of small and large companies. We need to work with the larger companies to develop the technologies and commercialize them. We need to provide seed money to the smaller companies to help them develop their new ideas.

Also an opportunity exists to link small companies which have the ideas with large companies which have the dollars, commercialization and marketing skills. This is a

role which is being played by the Bioenergy Program to an increasing extent.

DOMESTIC VERSUS EXPORT MARKETS

The issue here is, should R&D be supported to develop products which have export markets at the present time because of low domestic energy prices? In our view this is a legitimate role for the program under certain conditions;

- where we have a world leadership role in that particular technology;
- where there is also a domestic market perhaps in the future;
- where the primary objective is its energy impact on the domestic market in the future and export is a secondary objective;
- where we can tap into the resources of other agencies more involved with export markets, in this case CIDA, the World Bank, etc., because we are looking at developing countries where the need for these technologies is the greatest right now.

SHORT VERSUS LONG TERM R&D

Increased government emphasis on market driven R&D has resulted in a redistribution of funding for short term versus long term R&D. Short term R&D, 5 years or less, is nearer to commercialization, involves a lower risk, provides the Bioenergy program with better visibility if successful and normally requires a lower funding level. Long term R&D, 10 years or more, is generally more basic and therefore carries a higher risk, success is less visible because of the time factor involved and generally requires a higher funding level.

This issue also brings into question the traditional government versus industry role. Traditionally, the government's role has been to support long term, basic R&D. This appears to be changing.

The level of support is also a related issue since it should depend upon the risk involved. Less support on a percentage basis should be given for short term, low risk R&D.

In the bioenergy R&D program we are striving to maintain a reasonable balance between short versus long term R&D.

LEVERAGE / INTELLECTUAL PROPERTY

Current government policy with respect to cost-shared R&D contracts with industry is that if the government provides the majority of the funds then it owns the intellectual property. This policy is of course a disincentive to industry to cost-share. An emphasis on lower government cost-share will only increase the problem.

This problem can be particularly difficult where industry has spent a lot of time and money in developing a technology and seeks government support to complete a key element. In such a case the company would no longer have complete rights to the technology.

Our approach to this problem is to try to negotiate licencing arrangements up front as part of the contract to give the company comfort from the start. This approach of course increases the complexity of the contract negotiation and requires considerably more time and effort.

PROACTIVE VERSUS REACTIVE

This issue causes a real dilema for R&D managers. On the one hand reduced R&D budgets and the need to prioritize activities as well as consult with industry is forcing managers to be more proactive. On the other hand pressure to be more responsive to market opportunities may force managers to be reactive. That is, they are forced to respond to individual needs and could end up with a program that lacks direction.

Managers can try to deal with this dilema in a number of ways; they can be proactive in establishing technology areas and be as reactive as necessary within that area. For example, we might establish biochemical conversion as a priority area and be reactive to all kinds of proposals within that area; they can be proactive and keep a reserve fund for new ideas; they can refer reactive proposals to other programs such as the DSS UP program.

ENVIRONMENTAL PRICES / ENVIRONMENTAL CONCERNS

As already described, energy prices have dropped significantly. As a result, bioenergy technologies are having more difficulty competing. Energy security is no longer an issue; energy is no longer a priority.

Bioenergy technologies however, can have a positive environmental impact. Bioenergy can be part of the solution. There may be an opportunity for bioenergy to capitalize on the fact that environment is a number one public concern and is high on the political agenda.

A mandate problem does exist however, in that the mandate of EMR is energy and not environment.

ROLE OF BIOENERGY IN THE ENVIRONMENT

Bioenergy can have significant role to play in addressing some of the environmental concerns. One of the major environmental concerns relates to CO_2 build-up in the atmosphere and the resulting greenhouse effect on global warming.

Approximately 60% of these greenhouse gases being added to the atmosphere result from the production and burning of fossil fuels in the various sectors; industry, residential, transportation. This is the release of carbon which has been locked in the earth for millions of years. At the Changing Atmosphere Conference in Toronto last June, Canada agreed to develop a strategy to reduce CO_2 emissions by 20% by the year 2005.

Biomass is composed of about 50% carbon. This carbon is taken up as CO_2 from the atmosphere through photosynthesis as the biomass grows. This carbon is also released to the atmosphere as the biomass decomposes or is burned (CH_4 or CO_2). Provided biomass is replaced at the same rate it is consumed as a fuel, then bioenergy will not significantly affect the overall level of CO_2 in the atmosphere. In fact, an overall reduction of CO_2 levels will result if the bioenergy were replacing energy from fossil fuels. Also because biomass contains little or no sulfur or nitrogen, greater use of biomass for energy in place of fossil fuels, could help diminish the acid rain problem.

A greater use of biomass for energy whether in direct combustion as solid fuels in the industrial and residential sectors or as liquid fuels in the transportation sector could result in a decrease in the rate of CO_2 build-up in the atmosphere provided this biomass is replaced by reforestation, agroforestry or whatever method is appropriate. The general public would not look too kindly on the net removal of trees for energy or fuels.

It would be shortsighted to imply however that bioenergy does not have associated environmental problems. The combustion of biomass can produce high levels of particulates and other hazardous chemicals associated with incomplete combustion. Technologies are available which can control these emissions at acceptable levels. However the introduction of these technologies adds significantly to the overall cost. This is an area that requires further R&D attention.

CONCLUSION

An overview of bioenergy development in Canada over the past 10 years or so has been presented in the context of a changing policy environment; changing energy policy, fiscal policy, S&T policy and environmental issues. This changing policy environment has shaped and continues to shape bioenergy development in this country.

It has certainly been an eventful and interesting 10 years. There have been some remarkable technical achievements by Canadian researchers working in this area. In terms of energy contribution, bioenergy has made its mark on the Canadian energy scene over the past 10 years and it is here to stay. A 7% contribution to primary energy demand cannot be ignored.

Although energy supply is not the major driving force as it was several years ago, tremendous opportunities still exist. For example, opportunities exist for using biomass wastes for energy, whether they be sawmill wastes or municipal solid wastes, and at the same time solve a waste disposal problem.

Bioenergy can lead to significant regional and economic development. This has been the case in Atlantic Canada where the development of a wood chip fuel industry based on non-merchantable material has led to the creation of hundreds of jobs and millions of dollars worth of economic development.

Public concerns over the environmental effects of combustion of fossil fuels is forcing Canada and other industrialized countries to take a hard look at their energy supply options. A greater use of biomass for energy can be part of the solution - whether it be through direct combustion or conversion to liquid transportation fuels. It is assumed of course that the biomass is replaced at the same or greater rate than it is consumed.

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EED PROGRAM BUDGET

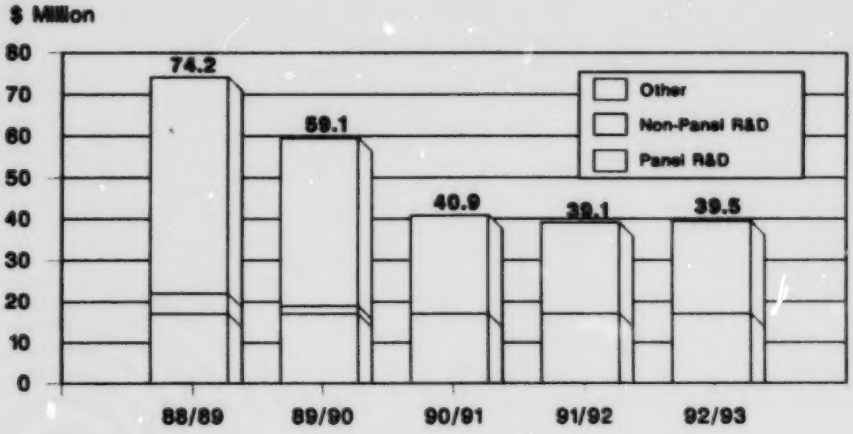

Figure 1. Five Year EED Program Budgets

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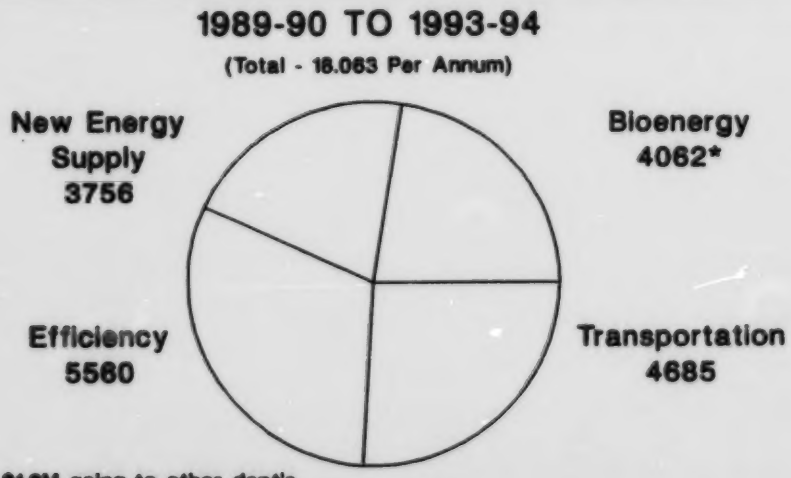
EED R & D BUDGET ($000's)



* Additional $1.3M going to other dept's.

Figure 2 EED R&D Budgets

ESTIMATED FEDERAL BIOENERGY R & D EXPENDITURES

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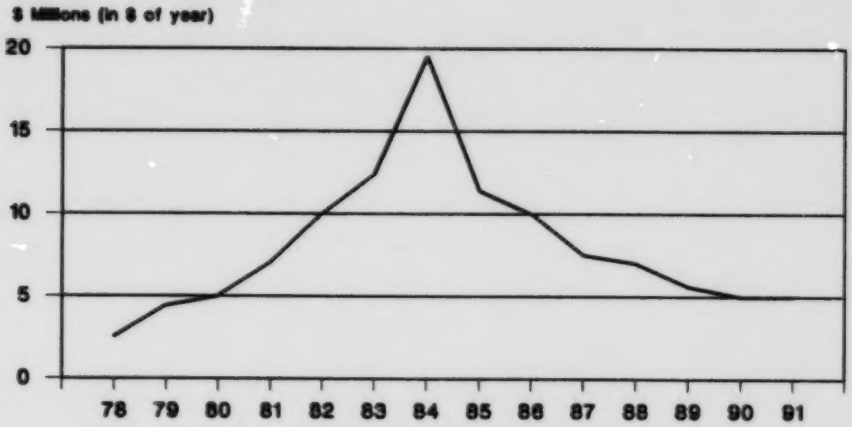

Figure 3. Federal Bioenergy R&D Expenditures

Allocation of Panel on Energy R&D Resources by Task & Major Energy Policy Statement

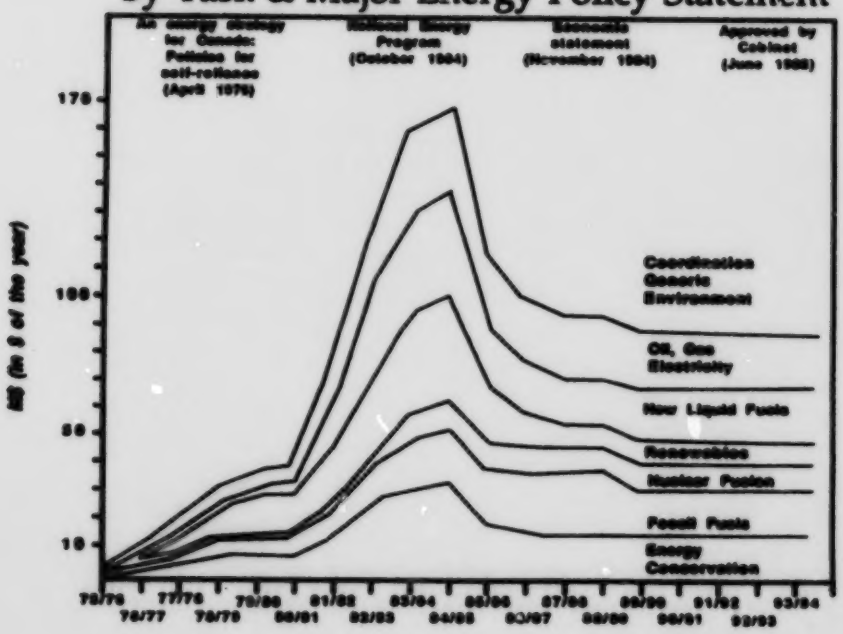

Figure 4. Total Federal Energy R&D (PERD) Budget

TEXT OF PLENARY PRESENTATIONS

TEXTES DES PRÉSENTATIONS DE SÉANCES PLÉNIÈRES

CANADIAN BIOENERGY R&D - 1989

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This is an overview paper of current Canadian federal bioenergy R&D activities and rationale in the context of concerted effort over the past ten years. This decade has seen dramatic changes in R&D funding, technology development, and scientific understanding of biomass as a source of energy and chemicals. Public concern for the environment, and shifts in government policy and economic and energy climate have also added their influence on changing research priorities.

Biomass production research has virtually eliminated all development of harvesting equipment while increasing effort on environmental impacts and improved silvicultural practices. Biomass handling and preparation has geared most of its emphasis in the past five years to meeting the needs of the current bioenergy consumer. Combustion research too has for a long time been commercially oriented, but has shifted in response to changing demand patterns and environmental protection needs, particularly in the residential and industrial sectors. The thermochemical and biochemical conversion areas were in their infancy in terms of development ten years ago, and have undergone the most dramatic changes in both progress and approach.

INTRODUCTION

As an overview, this paper describes Canadian federal bioenergy R&D activities while also giving a contextual flavour of the historical approach to R&D funding and strategies, the achievements, and the changes in outlook, events, and expectations that have occurred over the past ten years. The policy environment, once supportive in market intervention, has moved toward market orientation. This has also influenced R&D thrusts. Also addressed throughout the paper is the rise in global and national concern for our environment and some of the roles that bioenergy can play.

HISTORY OF CANADIAN BIOENERGY R&D

1988 marked the tenth anniversary of concerted bioenergy R&D in Canada. The Canadian Forestry Service launched a five year program in 1978, called ENergy from the FOrest, or ENFOR. At that time ENFOR was divided into biomass production and conversion sub-programs. Other departments such as Agriculture Canada (AC), National Research Council (NRC), Environment Canada (EC), and Energy Mines and Resources (EMR) had also added modest bioenergy R&D components to their existing programs.

Starting off with this initiative in 1978 of less than $4 million per year, funding for bioenergy R&D in participating departments rose rapidly to a peak of $22 million in 1983 and 1984 as shown in Figure 1.

By 1984, however world oil prices were softening considerably and NRC, the lead bioenergy performer, withdrew entirely from the energy program. Agriculture Canada also phased out its program. EMR assumed the lead, having already established the Bioenergy Development Program (BDP) two years earlier with the transfer of the ENFOR-conversion program from the Canadian Forestry Service. 1985 and 1986 were tough years for bioenergy. Not only was the total federal budget pared down to approximately $8 million from its peak in 1984, but EMR was left to consolidate most federal bioenergy R&D activities and to manage the wind-down of many worthy projects that were simply no longer affordable.

The research community and an infant bioenergy supply industry were understandably upset with the downturn in funding prospects. Many research groups unfortunately left the bioenergy area in search of other interests. Others, who could find a fit within the downsized EMR strategic plans

drafted in 1985 and 1987 did one of two things: they found private sector funds (see Table 1) to maintain their pace of development; or lowered their expectations of large funding and early scale-up and commercialization. These were the only sensible options in a world where energy prices were low, albeit unpredictable, and yet "appeared" to be increasing at a slow rate over the next 20 years.

Figure 1

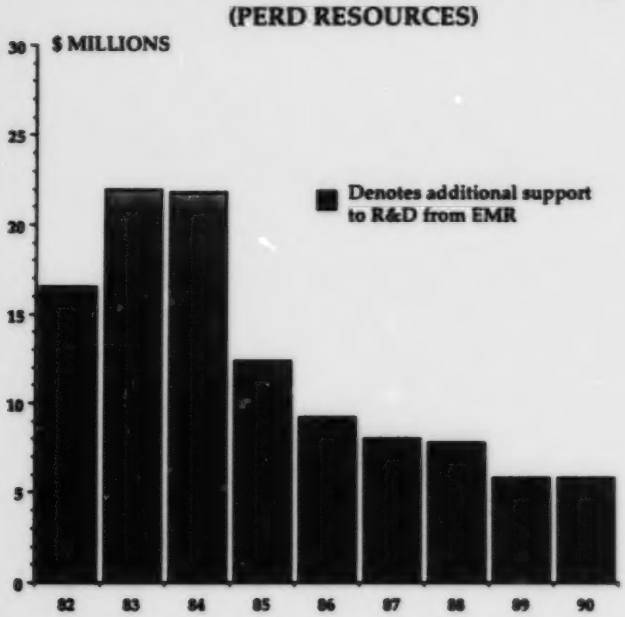


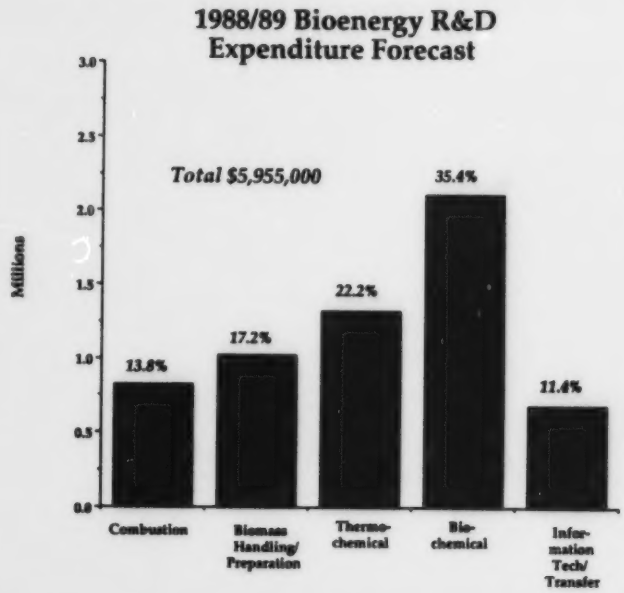
Table 1

	BDP R&D for FY 1988/89	*Total R&D for FY 1988/89
Combustion	821,000	900,000
Handling/Preparation	1,024,000	1,308,296
Thermochemical	1,353,000	1,626,122
Biochemical	2,106,000	2,844,016
Information/Tech Transfer	651,000	671,800
Total	5,955,000	7,350,234
IEA	60,000	450,000

*Includes Contractor's & BDP Share

The dramatic change in funding resources and energy prices had a number of profound effects on the approach to R&D. A number of research areas faced major adjustments. Except for the completion of the Biosyn project (described later), gasification R&D all but disappeared. Only a trickle of activity in upgrading research was maintained in the liquefaction area, while most effort concentrated on primary oil production and improved process configurations and efficiency. Although ethanol from biomass maintained a strong relative position in the aftermath of 1984 at over 30% of the bioenergy conversion budget, it actually suffered the most devastating adjustment in funding. In 1983, funding for ethanol research was as high as $7 million involving a wide variety of technology options. By 1989, as shown in Figure 2 under Biochemical Conversion, it has dropped to less than $2 million.

Figure 2



The most significant change in approach was through the realization that some processes, especially in the thermochemical and bioconversion areas, that had been developed to provide a single bioenergy product, were simply not going to become commercial until energy prices increased substantially to make them financially competitive. Therefore, effort was increased in value-added byproduct or coproduct development, especially in areas where proponents desired early commercialization rather than wait out the price of oil. Where there was less urgency in commercialization, the research was accepted as long-term, more basic, and less desirable for immediate scale-up.

The concept that biomass is a multi-component resource, more chemically analogous to petroleum than to coal, influenced the research approach of many investigators including both those who were on a long-term track, as well as those who were seeking early commercialization. Biomass could be fractionated, and the components processed separately. Alternatively, biomass could undergo a primary conversion, and the intermediary products derived from the various biomass components could then be upgraded separately. The bioenergy conversion R&D program was not restricted to "energy-only" products and co-products.

Funding for R&D in bioenergy conversion and production has stabilized over the last five years at approximately $6 million and $1.2 million per year respectively. The panic of down-sizing and consolidation of federal programs is now history. In this stability, one more, and perhaps the most important, approach in research has occurred. Collaboration! No longer are biochemical treatments viewed in isolation from thermochemical treatments. No longer are researchers with special expertise in microbiology working in isolation from their counterparts in chemistry and chemical engineering. The best of all sciences are being combined in process development strategies.

BIOENERGY R&D AND THE ENVIRONMENT

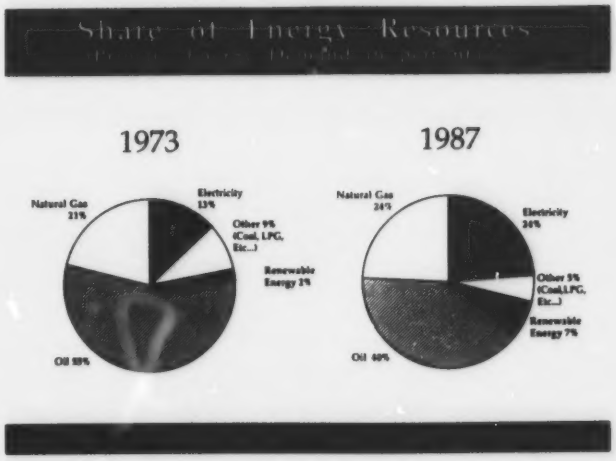
Revived public and political concern for our environment may well provide the most influence on bioenergy research strategies over the coming decade. The report of the Brundtland Commission, "Our Common Future" was released in March 1987 (1). The Montreal "Protocol on Substances that Deplete the Ozone Layer" was signed in September 1987. As a result of the World Conference on the Changing Atmosphere held in Toronto, June 1988, the world may have taken the first step to establish an International Law of the Atmosphere. Lead is being phased out of gasoline. Mexico city is blanketed in a cloud of pollution of crisis proportions. There is public outcry on acid rain, dioxins and the global warming effect of CO_2.

Bioenergy, on a global basis, can provide some answers to these problems particularly in helping to balance net production of CO_2 to the atmosphere while meeting future energy demands on a sustainable basis. The overall strategy must consider the careful replacement of nature's photosynthetic CO_2 sink by replenishing our forests as efficiently as possible through improved silvicultural practices and by advancing our technical and economic capability to produce biomass from intensive short rotation culture techniques. With respect to conversion technologies, care must be taken not to exacerbate the problem by developing processes that in turn create undesirable emissions and effluents, be they dioxins and particulates from waste incineration plants or waste water streams containing chemical pollutants. Examples of the kinds of research that have been emphasized recently include technologies to combust wood and wastes efficiently and cleanly in large plants or residential appliances, and treatments/upgrading of effluent streams from pyrolysis and ethanol production processes. Close-coupled gasification/electrical generation from wood and municipal wastes may even experience a come-back.

POLICY BACKGROUND

Since 1973, when OPEC induced the first major increase in world oil prices, Canada's energy demand picture has changed dramatically. A decline in oil's share from 55% in 1973 to 40% in 1987 has been accompanied by increased market share of natural gas, electricity and renewable (mostly bioenergy) energy sources (see Figure 3).

Figure 3



The Government of Canada launched a number of policy measures in the 1970's to improve Canada's energy self-reliance. Examples of early bioenergy initiatives included incentives to the forest products and other industries to use waste wood as a boiler fuel; a program for demonstrating new technologies in conservation and renewable energy; and a government wide strategic program on energy R&D, coordinated through an Interdepartmental Panel on Energy R&D (PERD).

During the latter part of the 70's and early 80's Canadian consumers were protected from the high international price of oil and gas by lower "made in Canada" prices. Although this helped to maintain economic growth there was less incentive to make cost-effective investments in bioenergy compared to other countries.

The second world oil price shock hit in 1979. The government responded in 1980 with the National Energy Program or NEP, a policy that encompassed unprecedented government intervention in the energy marketplace. Bioenergy R&D spending that

had been less than $4 million per year in 1979, skyrocketted to $22 million by 1983. Bioenergy demonstration budgets increased. A new off-oil program was implemented which provided taxable grants for more than one million homeowners to convert from oil to natural gas, electricity or renewable resources such as wood.

Then the bubble burst as OPEC started to increase oil production, thereby forcing the world oil price down again. At the same time in 1984, a new Canadian government decided that such a high-priced interventionist policy could no longer be maintained. They were also more inclined toward free market forces than was the previous government.

Energy, Mines and Resources established an interim three year program whereby large incentive programs were phased out and more emphasis was placed on information and technology transfer. Although bioenergy R&D decreased from $22 million to $8 million over this period, there was encouraged much greater cost-sharing by the private sector and increased emphasis on commercial oriented research.

The latest policy measure, called Energy Efficiency and Diversity (EED) was announced by the Minister of Energy, Mines and Resources September 9, 1988. EED is based on three broad overall objectives:

- to enhance Canada's industrial competitiveness;
- to improve the quality of the environment; and
- to ensure Canada's energy security.

How EMR's bioenergy R&D program fits within these objectives is described below.

FEDERAL R&D PROGRAMS

Since NRC and AC wound down their bioenergy R&D programs following the 1984 budget reductions, the Departments of Energy, Mines and Resources, Forestry, and Environment have taken on the major role in energy from biomass and wastes. The following sections describe these programs as they exist today.

ENERGY MINES AND RESOURCES CANADA

Bioenergy R&D Program Operating Principles

The EED initiative provides increased emphasis on commercially oriented R&D through its objective of enhancing Canada's industrial competitiveness. However, industrial competitiveness is not limited to a snapshot in time. In the context of the other two objectives, industrial competitiveness is also meant to provide a continuum of technologies that are judged to become world market competitive over time as demand for diverse, secure, and environmentally sustainable energy sources climbs.

By this definition, industrial competitiveness, improving the environment, and ensuring energy security, collectively, is a maxim that should be applied to technologies under development for near term commercialization as well as for medium to long-term application. Bioenergy R&D, supported by EMR, therefore spans the entire spectrum from basic applied research sometimes requiring fundamental research (e.g. developing new analytical methods or gaining fundamental insight of catalyst reactions with lignin model compounds) through to near term development.

For technologies that are targetted for near-term commercialization, there is an operating principle exercised that typically requires private sector cost-share. The cost-share may typically range from 25 to 75% or more depending on such general factors as the ambitions of the proponent to scale-up the process, the degree of technical risk (assuming that financial risk is acceptable), and the expectations of the private sector partner(s) in the research to acquire a favourable license from the Crown to exploit the technology.

Some research is difficult to categorize as exclusively long-term or near-term oriented. For example, many of the silvicultural and environmental research results from the ENFOR program are continuously applied giving rise to incremental improvements in increasing biomass energy supply potential as well as in forestry management. Forest management and operating practices are usually fairly slow to change.

Strategic Planning

Under a policy of non-intervention in the market-place, it has become incumbent upon Energy, Mines and Resources to direct closer scrutiny than in the past to planning critical R&D needs in the context of the overall commercialization process for emerging technologies.

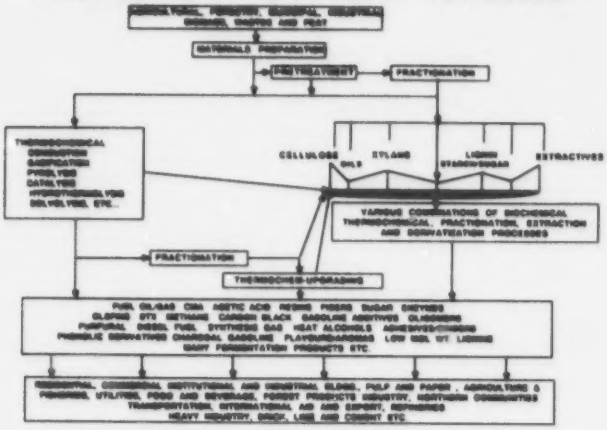
The planning group of the Energy Diversity Technology Division of EMR is developing a technique called "PAT (Prospective Applications of Technology) Planning", a term coined to describe the analysis of prospects and priority, and the development strategy, for emerging technologies.

A PAT, for which, in the bioenergy area, there could be thousands of combinations, is composed of essentially four parts: the feedstock resource, the conversion system, the array of products, and the market application. Figure 4 illustrates most of the combinations that are possible. Briefly illustrated, a PAT can be as simple as combusting wood chips in a stoker furnace to provide space heat for a greenhouse in New Brunswick. It can also be as complicated as coppicing poplar plantations, comminution of the wood, treating with steam and acid, fractionating, treating components separately in thermochemical and biochemical processes, fractionating intermediary products for further upgrading, and preparing final

products to enter different energy and non-energy markets in central Canada.

Figure 4

PROSPECTIVE APPLICATIONS OF TECHNOLOGY



When analyzing a PAT in its entirety, as much information as possible is collected, determined, or judged with respect to the following parameters:

- Stage or level of development,
- Estimated timeframe to bring technology through basic research, proof of concept, pilot development, demonstration etc.,
- Estimated total cost of development,
- Present and future prospective markets,
- Determination of cost or supply price of the products,
- Determination of financial and economic attractiveness,
- Determination of impact on industrial or regional development, employment, energy security and diversity, long term energy supply outlook etc.,
- Environmental impact of resource utilization, the conversion technology, and product utilization,
- Ultimate judgment of likely timeframe for commercialization.

There are a number of technical developments that have incurred a considerable investment of research dollars and personnel over the past ten years and require continued investment to bear fruit. Some of these technologies such as enzymatic conversion of lignocellulosics to ethanol and coproducts, or thermochemical conversion of wood to gasoline, fuel oil, and other chemicals are complex systems of several unit processes and varieties of products. Individual unit processes and products cannot legitimately be analyzed in isolation to give meaningful direction. As developments progress to the costly stage of scale-up, it becomes paramount that PAT planning be applied as soon as possible to determine answers to two critical questions: Rate of R&D expenditure? and Concentration of effort in R&D?

Bioenergy Development Program

The Bioenergy Development Program, or BDP, was initiated in 1982 when the conversion area of the Canadian Forestry Service's ENFOR program was transferred to EMR. The mandate was expanded to cover conversion of all bioenergy resources including forestry and forest products residues, agricultural, municipal and industrial organic wastes and peat.

Bioenergy Resources. The level of R&D effort targetted to address the above resources generally has assumed proportions appropriate to the "opportunity" for each resource to contribute to Canada's energy supply. The measure of opportunity is a somewhat subjective judgment that takes into consideration factors such as timeframe for commercialization; realizable potential in terms of partial market uptake in the near term and substantial market uptake in the long term; national potential, balanced with local and regional potentials; national environmental priorities such as finding alternatives to landfilling municipal wastes; and other economic or industrial/employment benefits.

Relative to other biomass resources, wood is the number one candidate as it is ubiquitous and abundant in Canada. In many cases (e.g. forest product industry residues), it is the most economically retrievable and usable. Notwithstanding wood's overall abundance, recent changes in forestry operations are causing a change in view of which forest residual resources are (or will be) available for bioenergy. Stands of hardwoods, previously considered unmerchantable and available for bioenergy, are now being increasingly used for pulp and paper production. Intensive harvesting in eastern Canada is exceeding the Annual Allowable Cut. Conversion process economics of proposed large scale plants such as enzymatic conversion of wood to ethanol are suggesting that short rotation intensive culture of poplar or willow is required to feed a 1000 tonne per day plant rather than collecting and transporting residues from the forest and forest products industries over long distances. On the other hand, recent changes in forestry operations toward whole tree harvesting or future concepts such as whole tree transportation and central refining may make lower cost tree components more accessible and affordable for bioconversion processes.

Municipal Solid Waste (MSW) claims less than 10% the potential that wood has in Canada but is ideally located and centralized in its collection. MSW continues to take on more importance in bioenergy R&D because of the public environmental concern over, and declining availability of, landfill sites. It is a difficult resource to handle as undesirable components such as batteries,

inorganic materials, and plastics must be sorted out prior to many bioconversion processes.

So far, apart from recycling, incineration has been the only reliable option open to municipal authorities to reduce pressure on the dwindling number of nearby landfill sites. Guidelines and regulations that are being formulated under the new Canadian Environmental Protection Act may require emission controls for incineration that are prohibitive in cost for all but very large combustion plants. In the R&D sense though, development of novel thermochemical or biochemical processes may provide other viable and environmentally attractive options for the future.

R&D focused on the treatment of MSW must be carried out in the context of an overall strategy of waste management, which is like taking aim at a constantly moving target. For instance, Recycling, Reducing, and Reusing are popular themes of today's waste management but the strategy is not at all clear. Parts of the country have adopted successful programs of refuse sorting at the household. Others have not. The success of refuse sorting of plastics, bottles, cans and newspapers has in some areas created a market glut problem for recycling operations. If recycling is not market driven, surpluses will continue to be forced back to landfill. The social stigma exemplified in the expression "Not In My Backyard (NIMBY)" continues to plague efforts to locate garbage treatment plants of any type in urban areas. There is no answer yet. If there were, strategic planning of R&D would be straightforward. It is not!

Municipal and industrial liquid wastes, though small in energy magnitude, present some near term energy opportunities. These are, and will likely continue to be, environmentally, more than energy, driven.

Canada boasts the second largest holdings of peat resources in the world, next to the USSR. However peat is generally deemed as very expensive to recover/utilize due to its usual remote locations and its difficulty in handling and processing. In addition to a long-term national interest in this resource, some provinces are supportive of early regional and site specific opportunities. There are environmental forces that might be described as a "Preservation of Canada's Wetlands Movement" that are raising public concern over peat exploitation for horticultural or industrial purposes at the expense of destroying unique habitats for birds, animals and plants.

Agrifood residues (e.g. straw, chaff, manure, and food processing wastes) have a theoretical potential contribution in magnitude similar to MSW. From the non-residue side, grain and oilseed resources have been perceived as a popular bioenergy opportunity by the farming community as a possible buffer when crop surpluses and sagging grain prices occur. Historically though, this popularity surges and wanes along with the vagaries of prices and surpluses.

Technologies

As illustrated in the preceding Figure 5 (Prospective Applications of Technology), processing systems are becoming more mature and multidisciplinary. The traditional technology areas of combustion, biomass handling and preparation, thermochemical and biochemical conversion are evolving into a melting-pot of overall conversion systems that capitalize on the unique chemical characteristics of all biomass components. Nevertheless, it is awkward to describe the program in terms other than the four major technology areas. The following provides a brief description of each area along with several examples of project investigation for each.

Biomass Handling and Preparation. Biomass handling involves the physical movement of biomaterials (including biomass and intermediary products) but without intentional alteration of the material characteristics. Operations can include translocation/conveying, transportation, storage, metering and feeding. It also includes the measurement of biomaterial properties such as size, moisture content, viscosity, temperature, acidity etc.

Within the area of preparation are those operations that improve the quality of biomass or intermediary products. Physical properties of the material are generally altered, although chemical changes may also occur. Major categories of operations include size segregation; mixing; solid-liquid, gas-liquid, or liquid-liquid separation; drying; extraction; comminution; and compaction/densification.

Individual biomass resources often have unique requirements of handling and preparation that depend also on the bioconversion treatment proposed. Biomass materials differ in state (solid, liquid, slurry, wet, etc.). Following primary processing, materials, or their fractionated components, may become homogeneous but may also have acquired other special handling requirements if they have become acidic, basic, or more biodegradable.

The vast diversity of biofuel and intermediate product forms, qualities and characteristics demands the attention of research and engineering skills. That attention, however, can easily be left for granted amidst the higher profile of the conversion aspects of process development and application. Fortunately over the years, biofuels handling procedures, at least for combustion applications, have matured to systems that are workable, if not ideal. Less than ideal systems have been adapted from existing equipment used in other sectors such as coal, ore or grain handling.

Since combustion is by and large the major prevalent bioconversion process used today, high priority is given to improving performance and emissions by addressing fuel quality. Boilers operate better on a more uniform fuel. Unfortunately, biofuels such as hog wastes do not nearly receive the same attention and effort that analogous specification fossil combustion fuels from petroleum and gas receive. If part of the fuel is too fine and the system is not specifically designed for fines, the emissions usually increase radically and plugging problems can occur. The second most critical area that R&D can address is efficient hog fuel dewatering. Hog fuel is typically over 50% moisture, the burning of which incurs severe thermal penalties.

Logging slash and sort yard debris represent a large potential bioenergy contribution, yet this resource is largely unutilized at present energy prices. It would require more pressure from environmentalists and provincial authorities, and a significant change in economic factors before the private sector entertains any R&D on the handling and preparation of these materials. Both resources are accessible through development of collection equipment in the case of logging slash, and in segregation equipment for separation of inorganics (mostly soil) in the case of sort yard residues. In the early high energy price days of bioenergy R&D there was considerable investment in such equipment development. Perhaps the market was not then ready for the resource or the equipment. Whatever the reason, the commercialization prospects withered.

As the commercial orientation on R&D was increased since 1984, the obvious area to receive increased support was in handling and preparation of biomass associated with "commercial bioenergy", predominantly industrial boilers, and small commercial or institutional automated chip combustion systems. The change in strategy may have done little to increase the vast potential prospects of forestry residues, but it resulted in several emerging commercial success developments that are being well received by the marketplace. Key areas of commercial interest and/or uptake of R&D are exemplified in an automated chip handling and feeding system; dewatering of hog fuel for better combustion control, efficiency and emissions reduction; a mass flow bin design; a non-consolidating feeder; a vacuum drum separator; a pneumatic conveyer; a continuous moisture sensor; a pulp and paper sludge dewatering device; low power grinding of biofuels to fine powders for injection into retrofitted oil burners; and even the adaptation of a manure spreader for woodchip handling.

Many of the developments mentioned above are applicable as well to other bioconversion technologies in the thermochemical and biochemical areas, but it was combustion applications that really provided the impetus for their development.

Areas that will likely receive increased attention over the next few years are specific handling and preparation problems associated with municipal solid waste. Some of the technologies mentioned above will find application, but MSW is a considerably different biofuel than wood. Peat also requires special handling considerations depending on its method of mining and processing.

To date, the lack of development of handling procedures for intermediary products (solids, liquids, gases) arising within thermochemical and biochemical process configurations or other ancillary operations such as ash handling from gasification, has been a more or less conscious oversight. Engineering development can usually catch up quickly to scientific development once a concept is proven technically, and even quicker if proven economically. This is a gamble that researchers take to avoid needless engineering effort on ancillaries to processes that may or may not come to fruition. It is always intended by process developers however to jump-start engineering solutions when appropriate. It is believed also that, by that time, commercial interests should also be eager to share the cost of these final add-on developments.

Combustion. Focus of effort includes improvements of industrial, commercial, institutional and residential combustor performance and emissions, as well as improvements to biofuel quality such as moisture content and size uniformity which directly impacts the combustion process (see Biomass Handling and Preparation). Combustion with heat recovery applications, particularly in the residential and industrial sectors, is largely responsible for the bioenergy contribution of 6.5% (541 PJ/yr) of Canadian primary energy supply. All remaining non-combustion and other renewable technologies in solar, wind, geothermal, low-head hydraulic, etc. make up less than 0.5%.

The continued financial attractiveness of this bioenergy option, especially in eastern Canada and within the forest products industry, is maintaining its expected growth despite low competing oil prices. However, as with the environmental concern described above for municipal wastes, there is increasing pressure to establish national guidelines and provincial regulations on wood combustion emissions in all sectors of the economy. For the time being at least, acceptable performance and emissions control standards for residential appliances appear to be well in hand of the Canadian Standards Association which is aligning guidelines with those of the U.S. EPA. The situation for industrial boilers is less clear.

EMR's "National Study of the Viability of Using Wood for Domestic Heating" (5) estimated that over two million households in 1984 (almost one in four) were burning 7.5 million cords of wood annually, the equivalent of 171 PJ of primary energy supply. These residences burn roundwood in either stoves or

central heating systems (approximately 30 to 50 kW). There are a number of wood chip and pellet fuelled systems in the 300 KW to 1 MW range that have demonstrated their ability to operate on a fully automated basis, but there is a gap in availability of equipment which has been proven for Canadian non-residential applications in the 50 to 300 kW size range.

Preliminary analysis shows that, in addition to a few current selected sites in Canada, automated particulate-fuelled systems for commercial, industrial, and institutional space heating will become attractive at world crude prices of $20-25/bbl, for pellets, and $25-30/bbl, for wood chips.

Most of the small-scale combustion R&D has been oriented towards improvements in safety and performance, and the reduction of emissions (efficient designs, catalytic appliances etc.). While most of the safety work has related to stoves, the performance work has been emphasized on roundwood and chip-fired central systems, as well as retrofits to old oil-fed appliances. One EMR study involved the testing of ten central wood heating appliances. The seasonal efficiency of the best, the average, and the worst was 64%, 52% and 45% respectively. With a small amount of R&D, the best furnace was modified to achieve 79% efficiency.

In addition, EMR funded the development of a wood energy technical training manual. A nation-wide program of training courses based on the manual is being developed by the Canadian Wood Energy Institute. For the general public, EMR's "Residential Wood Heating: A Home-owner's Guide" (6) is available.

The current contribution of industrial biomass combustion to primary energy supply is 370 PJ/yr. Included are medium-scale systems of 10-40 GJ/hr and large scale systems greater than 40 GJ/hr (e.g. 40,000 lb/hr of steam). Most Canadian applications involve mature technologies which are commercially proven, technically sound and economically viable. However, new systems and new applications for existing technology are under development or being demonstrated. While market penetration of combustion technologies has been largely in the forest products industry, opportunities also exist in non-forest sectors such as utility systems and other industries with high energy requirements where low cost forest waste or waste biomass materials (e.g. packaging) are available.

Over 95% of all urban refuse is currently landfilled. Landfill however, seems to be systematically losing its charm as a waste management strategy. Landfill space in some urban centres is quickly running out. Groundwater contamination from uncontrolled leachate, and emissions of methane to the atmosphere as a contributor to global warming, or as a cause of occasional explosions, are concerns for an environmentally and safety conscious public. Some of these concerns can be alleviated by innovative design of new landfill schemes and by the recovery and utilization of landfill gas.

Waste incineration with heat recovery for district heating or electrical generation appears to be a sensible alternative to many planners. So far in Canada, there are only a handful of such facilities, generally termed as Energy from Waste or EFW plants. This option also, however, raises environmental concerns over the release of dioxins, furans, soot and other pollutants into the atmosphere. Whereas landfills are usually located outside of town, the ideal location for EFW facilities is usually within an urban area, adjacent to district heat customers. This leads to the familiar cry of "Not In My Backyard (NIMBY)" by local residents.

With the efforts of Environment Canada and the Canadian Council of Resource and Environment Ministers (CCREM) to establish strict guidelines and/or regulations on emissions from waste incinerators, there is a major decision yet to be made by R&D planners on whether to invest heavily in the development of cost-effective combustion and emissions control systems that will meet these guidelines when they are implemented, or rather to concentrate R&D efforts on less conventional and possibly cleaner technologies in the thermochemical and biochemical area.

A sampling of on-going combustion R&D projects includes the following:

Canadian Resourcecon - developing a cost--effective cogeneration unit for sawmills using an indirect-fired gas turbine.

ORTECH International - operating a facility for the independent testing of fuel preparation processes and biomass combustion system components.

Prairie Fibre Inc. - investigating the feasibility of utilizing agricultural biomass such as flax shives, chaff and straw, and lumber wastes from adjacent areas in alfalfa dehydration plants.

Sandwell Swan Wooster Inc. - developing mathematical design tools for improved gas mixing in Kraft recovery boilers and wood waste fired boilers.

MacLaren Plansearch - reducing the data from the highly successful past research on four wood boiler units into a form useful to boiler manufacturers and operators.

Unigec Inc. - studying the feasibility of installing a system to co-incinerate MSW and industrial coke dust.

Environment Canada - support for the National Incinerator Testing and Evaluation Program in its assessment of air pollution control technologies suitable for the control of emissions from municipal energy from waste incineration facilities.

ORTECH International - developing recommendations

for appropriate efficiency and emissions control technology for small to medium scale commercial and industrial biomass combustion systems.

B.H. Levelton & Assoc. - providing a data book of systems for burning MSW and obtaining cost and performance data on all such combustion systems.

Research and Productivity Council - evaluation of circulating fluidized bed combustion for the recovery of energy from pulp mill waste.

PEI Energy Corporation - inspecting 20 chip-fuelled combustion installations in the range of 300 to 8000 kW for the purpose of documenting design faults that could be avoided in future designs.

Thermochemical Conversion. No area of bioenergy R&D has undergone as much dramatic changes in strategy over the past ten years as thermochemical conversion has.

During the late seventies, using approaches akin to coal gasification and liquefaction, researchers strove to develop technologies and products that could substitute for natural gas and fuel oil. Ambitions only briefly flourished to upgrade crude bio-oil to transportation fuels products. Gasification demonstration plants were being built at an unprecedented pace in the U.S.A. Canada was embarking on a $21 million development of Biosyn, a ten tonne per hour oxygen or air fed, pressurized, fluidized bed gasifier to produce synthesis gas for fuel methanol production. Scientists were only beginning to understand the fundamental differences between processing coal and biomass. Canada, USA, Sweden and Finland were making plans to design and build a common Biomass Liquefaction Test Facility (BLTF) under the auspices of the International Energy Agency.

Then, almost as if to thwart the enthusiasm of developing alternatives to petroleum, the OPEC nations increased oil production and major new finds were developed. The world price of petroleum started to drop and renewable energy R&D budgets in Canada were decreased radically by 1984, as they were elsewhere worldwide.

Too many commercial gasification attempts had failed technically or financially as premature showcases of immature technology. BIOSYN continued, but interest in the project as a potential supplier of transportation fuel waned. That commercial strategy gave way to redirecting the technology to operate in the air fed mode as a gas producer to generate electricity for third world markets.

By the end of 1984, only low level research on upgrading of pyrolysis oil to gasoline was evident. The rationale for liquefaction development as a mid-term opportunity (e.g. 10-15 years) was adjusted to a long term option for the 21st century.

It was science, more so than engineering, that possibly saved this research area from extinction in the face of severe budget constraints. It is true that Canadian liquefaction researchers and research managers, most of whom are engineers, frantically scurried to establish and improve engineering design data for primary oil production, but it was the "chemist" element in those laboratories and government offices that refused to ignore quiet discoveries that were being made on the analytical bench. Biomass and its primary oil products were quite dissimilar to coal. It required different approaches to conversion. Biomass could be pretreated and fractionated prior to processing. Primary oil could be fractionated and possibly refined in a fashion analogous to petroleum. It contained a variety of high value specialty chemicals as well as commodity products. Phenolic derived components of oil, presumably arising from the lignin fraction of biomass, could be upgraded to high octane gasoline. Activated charcoal and carbon black were identified as value added coproducts. Process conditions could be adjusted to favour the production of precursors for polyolefins or polymer gasoline. Pretreatments were discovered to radically shift chemical pathways from "oil-like" components to sugars, possibly suitable for biological conversion applications. One particular hybrid of poplar was found to yield much higher than usual quantities of phenol. Investigators began to pay attention to waste water effluent problems by applying additional catalytic hydrotreatments to recover other value added fuel or chemical products, or recovering acetic acid in the form of CMA, a road/bridge de-icer, while at the same time making these effluents suitable for disposal in waterways. Developers of processes in the biological conversion area began to request that thermochemical researchers assess the conversion of lignin coproducts derived from steam pretreatment of biomass, the carbohydrate fraction of which, was destined for microbial conversion. Multi-disciplinary collaborations had begun to materialise.

A world of opportunity is further widening now with the application of some of these techniques to low quality plant oils, waste animal fats, oil derived from sewage sludge, and tall oil from Kraft pulping. Biomass thermochemical process development is now being applied as well to some to the environmental problems in our society such as urban refuse, waste tires and other industrial organic wastes.

The achievements, approaches, and a detailed review of on-going research in Canada would be too lengthy to include in this paper, but a fairly comprehensive overview (7) was presented at the IEA Research in Thermochemical Biomass Conference, Phoenix, Arizona in May 1988, and is available from the Energy Diversity Technology Division of EMR.

Summarized in brief, but not all-inclusive, are the following on-going studies:

Low severity liquefaction of wood using aqueous hydrogen iodide at McGill University.

Steam pyrolysis or hydrothermolysis of wood; and fundamental studies of catalytic treatment of lignin model compounds at the University of Toronto.

Vacuum pyrolysis of wood, steam fractionated lignin, MSW and waste tires; upgrading of pyrolysis oil; and investigation of separation techniques of fine chemicals at Laval University.

Atmospheric flash pyrolysis of wood, wheat chaff, and peat plus several process variations of pyrolysis and upgrading to gasoline, chemicals and sugars at the University of Waterloo.

Pressurized solvolysis of wood and peat; combinations of steam fractionation, solvolysis, and acid/thermal/shear treatments of biomass; a variety of fundamental studies on conversion of lignin monomers and model compounds; and the development of novel analytical methods at the University of Sherbrooke.

Thermal and catalytic cracking of pyrolysis oil products; and pyrolysis of raw biomass in a Rapid Thermal Processor (RTP) at Ensyn Engineering, Ottawa.

Development of a small to medium scale, two stage gasifier capable of producing a clean gas from wet wood waste at Heuristic Engineering, Vancouver.

Biochemical Conversion. Bioenergy has made substantial market penetration in sectors of the Canadian economy that can economically substitute biomass combustion for fuel oil applications. The transportation sector, however, has been almost untouched by alternatives except for minor uptake of propane, natural gas, and alcohol blends with gasoline. No other sector in Canada or the U.S.A. is as unclear as to its future options as transportation is.

The USDOE has published an excellent, albeit preliminary, discussion of alternative fuel use in the transportation sector (8). In the report, CNG and electricity are dismissed for vehicle cost and infrastructure reasons, at least for the 1990's timeframe. Efforts to develop lower cost ethanol from biomass production technologies are recognized, but it notes that "none has yet reached large-scale commercialization." Most of the discussion centres around methanol from natural gas, but notes that any sizable market penetration (e.g. California) would, in theory, consume most available proven world reserves of gas, assuming that other countries did not opt for methanol as well. Methanol from coal appears to be feasible in terms of meeting a large demand, but costs for production may be as prohibitive as ethanol is currently believed by many to be.

The report suggests though, that in the absence of any single clear choice, there are advantages in starting any major shift to a number of alternative transportation fuel options by adoption of Flexible Fuel Vehicles (FFV). Without a clear indication of our future, and in the absence of clear direction through analysis and policy, ethanol from biomass and wastes would likely be as viable an option during the next 50 to 100 years as several other transportation fuel products (including gasoline) would be in a society that drives FFV's.

The viability of ethanol in such a society would be contingent upon its capability to be competitive with gasoline, methanol from natural gas, propane, etc. An R&D planner who has seen the rapid technical progress of the past four years and who is confident in the promise that biotechnology offers would argue that ethanol from biomass is an R&D option that an environmentally aware society cannot afford to discard.

There are three major areas that require cost improvement through R&D:

1. The conversion of the carbohydrate (cellulose and hemicellulose) fraction to ethanol and/or coproducts;

2. The recovery, utilization, and/or conversion of the lignin fraction to value-added specialty chemicals (in the short term) and commodity chemicals (in the long term); and

3. The supply of inexpensive biomass delivered in sufficient quantity to feed a large ethanol plant (eg. 1000-2000 tonnes per day), most likely from a nearby short rotation forest plantation.

The ENFOR program is tackling the latter area. Short rotation intensive management of forests, in a fashion similar to agriculture, would also serve well global interests of reducing net production of CO_2 to the atmosphere.

EMR's Bioenergy Development Program contributes a major portion of its biochemical conversion R&D budget to the treatment of hollocellulose and lignin, directly or indirectly, related to the production of fuel ethanol. The projects described below are only a representative sample of the types of R&D and technical interrelationships that prevail within BDP.

Iogen Corporation has gained considerable momentum in their research of steam fractionation, enzyme production and hydrolysis, and adhesive applications for lignin from wood. If their advances, particularly in the biotechnology area, can be maintained, this process likely has the best prospect for sustaining an economic advantage over other ethanol processes well into the future. Their work ranges from fundamental studies of hydrolysis (substrate-enzyme interaction) and design of an ideal cellulase complex, to more applied work in optimised enzyme production, pentose fermentation, lignin applications, and an engineering design of an automated fill value for

their steam reactor. They have been working in collaboration with others such as M. Wayman at the University of Toronto on pentose utilization, the thermochemical groups at the Universities of Waterloo and Laval, Mohawk Oil as a potential early customer of the technology, and scientists in Europe and the USA.

Biohol, a joint venture between St. Lawrence Reactors and Weston Research, is developing a process based on extrusion pretreatment, plug flow acid hydrolysis and Zymomonas fermentation. Their collaborators include the Universities of Toronto and Waterloo.

As a slight departure from mainstream ethanol from wood development are a number of research projects applicable to environmental or resource problems in the pulp and paper industry. Sources of softwood for pulp are becoming scarce in some areas of Canada, forcing the increased utilization of inferior hardwood fibre. CRSO Inc. is therefore developing a process to separate long hardwood fibre for pulp and short fibre for ethanol production. Forintek, in collaboration with Tembec, a sulphite pulp mill, is developing the capability to ferment all carbohydrate fractions of sulphite liquor from mixed hardwoods and softwoods. B.H. Levelton & Assoc. is studying the merits and difficulties of coupling an ethanol plant to a saw mill.

All of the above are linked technically, if not contractually, to research in other Canadian laboratories. Queen's University is working with Wardrop Engineering to develop an extractive fermentation applicable to fuel ethanol production from all sources. The University of Guelph is developing an ethanol sensor that would be applicable to fuel, industrial or beverage alcohol fermentations. B.C. Research, Forintek, and the University of Sherbrooke are investigating characterization and applications of lignin. Canviro Consultants, in addition to its monitoring of anaerobic digestion facilities in Canada, is conducting anaerobic treatability studies of waste streams generated by ethanol from sugar, starch and cellulose processes.

Information Transfer

A little over 11% of the BDP budget provided through PERD is expended on information transfer activities. During 1989/90 this will be supplemented by additional funds in line with EED objectives. Information transfer activities of the past such as the biennial Canadian Bioenergy R&D Seminar, and dissemination of contract research reports, brochures, articles in trade and scientific journals, and other EMR publications will continue.

Added to this is a computer database, called Bioenergy Information and Technology Transfer System (BITTS), which is currently under development. The BITTS database will be composed of three main components:

1. Installations - information on non-residential bioenergy installations in Canada.
2. Studies - information on R&D projects in Canada.
3. Contracts - listings of potential bioenergy users plus sources of bioenergy technologies, products, and expertise.

The database is an all-important foundation. Equally important though will be the marketing of this information, not only to answer requests but to provide custom-formatted packages targetted to potential users of bioenergy technologies and products, be they selected from narrow or broad fields of the database.

FORESTRY CANADA

ENFOR - Biomass Production

The ENergy from the FORest (ENFOR) program is managed by Forestry Canada (formerly the Canadian Forestry Service). Initiated in 1978, it is a contracted out research and development program that deals almost exclusively with the assessment, production and growth of forest biomass for energy. The yearly budget since 1984 has stabilized at approximately $1.2 million. A five year strategic plan (3) and review of projects (4) conducted under the program are available from Forestry Canada. The following is a summary of the five year strategic plan. The main adjustment to this strategy that has occurred since 1987 is that the environmental impact assessment area has grown considerably.

1. Resource assessment

The primary task of assessing how much forest biomass is available in Canada has been largely completed. Reliable estimates have been made for the quantities of forest biomass in the country. The gross amount of forest biomass in Canada is over 26 billion oven-dry tonnes, the equivalent of 82 billion barrels of oil, though it must be noted that not all this biomass is accessible or available for energy purposes.

2. Improving biomass productivity

Most forest biomass theoretically available in Canada for conversion to energy occurs as harvesting residues from natural stands, as material removed during stand improvement operations, or as stands merchantable only for fuel. However, most of this biomass is located at a considerable distance from the southern, more highly populated, industrialized regions of the country where energy needs are greatest.

An alternative future source of biomass, particularly applicable to these latter regions, is forest plantations of fast-growing species, included poplars, willows and alders, raised and

harvested on short rotations specifically for energy production.

Other means of maintaining and improving biomass production are being investigated, including nitrogen fixation using species such as alders and seedling symbiotic relationships involving mycorrhizae. The results of such research elicit interest beyond purely bioenergy applications. In this way Forestry Canada's bioenergy research activities are also closely integrated with those aimed at satisfying more conventional forest management objectives.

3. Mechanization

In order to harvest, process and transport forest biomass efficiently, new equipment must be developed and tested, or modifications made to existing equipment. In the past, this was a major component of the ENFOR program. Several pieces of equipment for processing logging residues were developed and tested. A system for separating and comminuting usable biomass from west coast logging sort yard debris was developed. A machine for harvesting and chipping non-merchantable brush stands was successfully tested.

4. Environmental impact

Harvesting forest biomass for energy involves a much more intensive and complete removal than conventional harvesting, and could have potentially serious adverse effects on nutrient cycling, soil stability, wildlife habitat, and other components of the forest ecosystem. These impacts are under continuing study. Considerable effort has been devoted to the development, calibration and application of the FORCYTE computer simulation model, designed to evaluate the long-term effects of intensive biomass harvesting on soil fertility and biomass production. FORCYTE also simulates the effects of most other forest management practices, thereby providing benefits in other fields of forestry research.

5. Economic studies

Socio-economic and institutional factors relating to the utilization of forest biomass for energy have been investigated. These include domestic fuelwood supply and demand, the feasibility of integrating biomass harvesting with conventional timber harvesting and forest biomass harvesting cost/benefit relationships. Economic forecasts and energy analyses have attempted to project the role of forest biomass within overall energy strategies. The relevance of some of these past economic surveys and analyses have, however, changed with the changing significance of the various components of the total energy picture, such as oil prices, fuel alcohol markets, and the overall forest industry economic situation.

ENVIRONMENT CANADA

Anaerobic Digestion

Environment Canada's Wastewater Technology Centre in Burlington, Ontario, annually receives $150 K through PERD to supplement their in-house research program on anaerobic waste water treatment. The laboratory is well equipped with some 13 pilot scale reactors, computer control and bench facilities. Since 1984, their work has concentrated on full treatment of complex and difficult to treat effluents from the pulp and paper industry, particularly those from TMP (thermomechanical pulping) and CTMP (chemithermomechanical pulping) mills. Another critical area of their research, from an environmental viewpoint, is the anaerobic treatability of chlorinated organic wastewaters from Kraft bleach plants. All of this work is done in close liaison with pulp and paper companies and other research institutions.

Oil from Sewage Sludge

Canada produces 500,000 tonnes of sewage sludge per year, the disposal of which is awkward and expensive. Sewage sludge is not a large bioenergy resource but disposal averages about 50% of a municipality's cost of operating a waste water treatment plant.

The Wastewater Technology Centre began bench scale research in 1982 after examining a technology at Tubingen University in Germany. By 1986, a 1 tonne per day pilot plant reactor was up and running at the Hamilton-Wentworth Sewage treatment plant. The technology is now about to enter the commercial demonstration phase with the recent announcement by the Governments of Canada and Nova Scotia to build a 25 tonne per day plant at Halifax. Funding for research and development support from PERD continues at a level of about $300 K per year.

INTERNATIONAL ENERGY AGENCY (IEA)

Eleven member countries of the IEA signed a three year cooperative R&D Agreement on Bioenergy May 1, 1986. It was a continuation of the former Forestry Energy Agreement. Member countries include Canada, U.S.A., UK., Sweden, Finland, N.Z., Ireland, Belgium, Denmark, Austria and Norway. The Agreement has been modified and extended an additional three years as of January 1, 1989. Italy and Japan have joined recently, and several others, including Spain, Switzerland, the Netherlands, and the EEC, have expressed interest in doing so.

Over the next three year period there are three Tasks, one each in Biomass Production, Biomass Harvesting/ Transportation, and Bioenergy Conversion. In principle, each country signs the overall Agreement and participates in specific Activities within one or more Tasks. Joining an

Activity commits the country to provide a nominal core contribution of funds to the management of the Activity. The bulk of the work however is done by each country through their national programs as so-called "in kind" support.

The Conversion Task contains nine Activities as follows, the first seven of which involve EMR:

Bioconversion of Lignocellulosics
Thermal Liquefaction
Municipal Solid Wastes
Gasification
Conversion Data Bases
Standard Analytical Methods
Combustion
Conversion of Straw
Wastewater Treatment and Analysis

Forestry Canada participates in the other two Tasks. In Biomass Production, research conducted on short-rotation forestry for energy deals with species selection, evaluation, breeding and clonal propagation of promising strains, water-use efficiency, nutrients, management practices, environmental impacts as well as mechanization. The Biomass Harvesting Task concentrates on the development of technology and systems to harvest forest residues, and small trees or thinnings for energy as well as the storage, drying and handling of forest biomass.

The types of interaction and collaboration vary, but typically involve information exchange, often through computer communication networks, round-robin experiments, or joint techno-economic assessments. They almost always culminate in a yearly workshop to discuss progress, problem solving, and planning the following year's work.

Total direct cash funding to the IEA from member countries varies each year but is typically between $50K and $200K per country depending on the number of Activities joined.

IEA membership, at a relatively low cost to each country's funding resources, provides an enormous leverage and early access to other countries' raw information. It provides Canada with a window to evaluate technologies in areas where our programs are weak. It is effective in the areas of long-term research to openly share information and collectively solve technical problems or controversies. Finally, it provides an excellent forum to showcase our leading technologies and allow them to be compared to potentially competing technologies. By so doing, their future promotion to external markets is enhanced.

INTERNATIONAL BILATERAL AGREEMENTS

Canada has a number of bilateral agreements on science and technology that are either government-wide, or directly between corresponding Ministries of Energy or their equivalent. The four of main interest to bioenergy are those with the European Economic Community (EEC), the U.S.A., Sweden and Japan.

The specific collaboration with the EEC is in the area of pyrolysis of biomass. Two Canadian technologies that have caught the interest of the European LEBEN (Large European Biomass ENergy) project are University of Waterloo's Flash Pyrolysis and Laval University's Vacuum Pyrolysis. A comprehensive description of the European program and the proposed collaboration on R&D and scaled-up demonstration was presented by G. Grassi at the IEA sponsored conference on Research in Thermochemical Biomass Conversion held in Phoenix, Arizona, May 1988 (2).

The Canada-U.S.A. Memorandum of Understanding between our respective Departments of Energy provides a framework for several informal arrangements of collaboration in a broad range of energy R&D. Although no bioenergy specifics are articulated in the Agreement, exchange of information and personnel between Canadian and American laboratories is fairly routine. As examples of other collaborations, EMR's Bioenergy Development Program and USDOE provide matching funds of about $50K per year each to SERI (Golden, Colorado), in supplementary support to the IEA Activity on Standard Analytical Methods. In another project, selected Canadian primary pyrolysis oils are sent to PNL (Richland, Washington), for catalytic hydrotreatment upgrading studies/evaluations. In yet another, selected U.S. primary pyrolysis oils are included for comparison in the centralized analysis project at B.C. Research in Vancouver. SERI also provides some analyses as a sub-component of the B.C. Research analysis project on Canadian and U.S. oils. Larry Douglas of Entropy Associates Inc, a former USDOE field program manager, is using some of the tools he developed in probability and financial analyses, while at SERI, on Canadian technologies including enzymatic hydrolysis of wood to ethanol.

The Canada-Sweden Agreement on Science and Technology has been inactive for some time, but plans are underway to develop a joint government-private sector project on acid-based hydrolysis of biomass to produce fuel ethanol.

Similarly, the Canada-Japan Agreement has been relatively inactive in the bioenergy area except for information exchange. Most of the collaboration to date has been through the IEA Bioenergy Agreement in the bioconversion of Lignocellulosics Activity. The area of thermochemical treatment of biomass and wastes might be a good choice for future bilateral discussions.

CONCLUSION

Since 1978, Canadian bioenergy R&D funding levels have changed radically in response to energy prices and policies but have leveled off since 1986

and are intended to remain stable over the next five years.

The past ten years of bioenergy R&D have seen continuous adjustments in approach most notably in the areas of biomass fractionation and multi-disciplinary research collaboration. Modifications in the planning of R&D will continue as research milestones are achieved and external influences, such as global concern for the environment and energy economies are felt.

Bioenergy is an important option for Canada's environmental future, industrial development, and energy security. R&D is required to address technical barriers to commercialization and information transfer is required to address non-technical barriers.

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BIOMASS, BIOENERGY AND AGRICULTURE IN EUROPE

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It is not widely recognised that renewable energies currently contribute about 10% of Europe's energy of which biomass contributes 2-4%, equivalent to 20 to 40 million tonnes of oil or about 1/2 to 3/4 million barrel of oil a day. New experience gained could make it possible that by the year 2010 the contribution of renewable energies may possibly reach 25% of Europe's energy production of which biomass could provide 10%. This could make a significant contribution toward energy self-sufficiency, and at the same time enhance the environment by reducing fossil fuel use and thus contributing to amelioration of global warming by helping to reduce CO_2 build-up in the atmosphere.

Biomass energy production and use is increasingly seen as closely linked with solving agricultural problems of land use, food surpluses and forestry. Biomass can also contribute both to rural development, particulary maintaining employment, and to help in solving Europe's agricultural problems. The changing perception of the role of biomass energy over the past 4 years has resulted from lowered energy prices, pollution and environmental concerns, and the need for structural reorganization of agriculture.

INTRODUCTION

Biomass is the world's fourth largest energy source, representing 14% of the world's primary energy demand (table 1). Biomass fuels also represent the dominant energy source of developing countries, providing 35% of their total energy demand. The use of biomass on a large scale is not confined to the developing nations. In the USA today biomass contributes nearly 4% of their primary energy, more than produced by nuclear energy. In Europe, it is generally accepted that about 10% of its energy requirements could be met from biomass by the end of the century. At present biomass contributes 2-4% of the EEC's primary energy demand.

Over the last four decades in Europe better management techniques, breeding programmes, the introduction of new technologies and increased chemical and energy inputs, together with the creation of the Common Agricultural Policy (CAP), have turned a situation of agricultural deficit and a goal of self-sufficiency in agricultural production, to a problem of large crop surpluses. The EEC is faced with the need to adjust its agricultural policy in order to achieve a number of objectives difficult to reconcile: disposing of surplus stocks and preventing their re-emergence, avoiding disturbance to international agricultural markets, maintaining individual farm incomes, conserving the fabric of rural society, and protection of the natural environment.

This paper gives an overall view of the bioenergy and agricultural situation in Europe with particular reference to the European Community (EEC).

EEC FOOD SURPLUSES

The creation of the CAP maintained prices of key agricultural products throughout the Community at levels in excess of those needed to ensure adequate supplies for European consumers. Three other underlying causes of over-capacity can be identified: a) the growth of output resulting from new technology; b) the inadequate growth of demand, and c) the pressure of politicians to avoid adjustments which are unpalatable.

Agricultural expenditure in the EEC went up from 11.9 billion ECU (1ECU= approx.$1.1US) (73% of the total Community Budget) in 1980, to 31.2 billion ECU (72% of the Budget) in 1988 (1). Within the EEC, barley production increased by 63% between 1960 and 1980; wheat and grain maize by 167%; cereal production (1972 to 1980) increased by 98% in France and 72% in the UK. The agricultural policy has helped to sustain returns to farmers, transferring much of the market risk of production to the public purse. The EEC has truly provided a large, open market, plus common standards on a unified front against international competition.

In the milk sector, it costs about £80M per week to store and dispose of EEC surplus stocks of butter and skimmed milk powder; beef cost £25M; the grain surplus some £45M. Rape seed oil is being subsidized at £500M per year. The total cost to the EEC of storing and disposing of all its surpluses is estimated at no less than £200M per week.(2). The estimated cereal surplus for 1988/89 is about 40M tonnes.

In addition to financial constraints there are other factors which also merit attention. a) **international agricultural trade**. The CAP is a

focus of hostility to the EEC by third country agricultural exporters. They argue that, by subsidising exports, the EEC has stolen their markets and impoverished their farmers; b) **farm incomes**. Despite the formidable cost, the CAP has not raised the incomes of the poorest section of the farming community to acceptable levels, this is because most of the cash transferred to farmers relates to production.The farmers who produce most receive most, small farmers receive little; c) **inequity among member countries.** The intra-EEC flow of resources, resulting from the CAP is a continuing source of tension because of the disproportionate contribution to the budget of the different member countries; e) **social and environmental issues** have become increasingly important but there is a lack of uniformity of approach among member countries.

As production and productivity are increasing steadily alongside a proportionally slower population increase, there is not likely to be any significant overall increase in either exports or local demand for crop products in which the EEC is already self sufficient. In fact data indicate that yields are still far below the theoretical potential, and although this potential may never be reached for agronomic, ecological and economic reasons, there is still scope for significant improvement. This would, if further steps are not taken, worsen the food surplus situation.

The Declining World's Foodstocks.

As the eighties draw to a close, climate change is being added to an already long list of environmental stresses that are undermining global food security. At the start of 1987 harvest, world grain stocks totalled a record 459M tonnes, enough to feed the world for 101 days. In 1989 this is likely to drop to 54 days of consumption, lower than the 57 days at the beginning of 1973. Stocks have declined sharply because food demand has continued its population-driven rise while production has fallen at a record rate. In 1988, for example, drought reduced harvests in the USA, Canada and China. Between 1950 and 1984, world grain output climbed from 624M.tonnes to 1,645M. tonnes and increased per capita grain production by 40%. Since then, output per person has declined each year, falling 14% over the last four years.(3).

In sum, overall food security is being threatened by two trends: a) the loss of momentum in the growth in output, particulary in developing countries, b) the warming of the planet. Thus, despite of the promises of new technologies such as biotechnology, this recent worriyng trend cannot be ignored.

ALTERNATIVES/SOLUTIONS

However in the EEC the persistent oversupplies of food and its increasing costs has brought about since the early 1980s a rethinking on agriculture. A scheme for the **set-aside** and also **extensification** of agricultural land was agreed by the European Council in February 1988 as part of the agricultural and budgetary reforms. These are two linked ideas. Extensification means farming less intensively in such a way as to produce less from a given area. One form, for example, is a scheme involving payments to compensate farmers for not using land to produce commodities in surplus, leaving it either fallow or using it for other purposes. The minimum premium will be 100 ECU/ha. per year and the maximum 600 ECU/ha. The provisions include: a) reducing production by 20% (cereals, beef and veal, and wine production); b) conversion of land to non-surplus products; and c) withdrawing land for production (by fallow, afforestation, or non-agricultural activities). The primary objective of both extensification and set-aside must be economic.(4). The set-aside is not designed to be implemented in isolation, but rather as a part of a total Community strategy for controlling agricultural production and agricultural support spending. Land withdrwan from the production of surplus commodities must not be allowed to generate a surplus of other agricultural commodities.

There are four main schools of thought with regard to the possible solutions of agricultural surpluses. Firstly, **to cut support prices** systematically until production is brought into line with market requirements. This may, however, bring widespread impoverishment to EEC agriculture, even with direct support to the most needy; smaller farmers and the less competitive will be forced out. The second popular solution is **to impose quota systems** on all the main agricultural products. This is an attempt to share out a finite volume of required production fairly among all producers, which is more preferable to price cutting. It does however pose difficulties because any quota system is by its nature inflexible and it is difficult to accommodate either differential efficiency or new recruits to farming and to know where to stop. The third option is called **disintensification**, that is, the reduction of the variable inputs so that crop yields or stocking densities per hectare are reduced. This approach appeals particulary to those who would wish to reduce the environmental impacts of fertilizer and pesticide usage. A further solution would be to provide attractive financial incentives for **alternative land use** to make use of the estimated 10-15M ha. of surplus farmland. These could include the conversion of land to non-food crops and diversification to non-agricultural uses; the conversion of land to forestry and other energy crops; the conversion of traditional food crops to non-food uses; the need to protect the environment.

For the land no longer required for the production of food, it could be put to a number of alternative uses: cultivation of fast-growing trees species, e.g. willows, eucalypts; cultivation of annual crops with high biomass yields to produce fuels; cultivation of high-yielding sugar and starch containing crops to produce natural substances for industrial uses and ethanol as a fuel ingredient; cultivation

of oilseeds to produce special vegetable oils for industrial use and to replace diesel oil; and cultivation of fibre plants.

BIOMASS IN EUROPE

Any consideration of biomass energy in Europe is complex since there are striking differences in indigenous energy resources, energy demand, population density, intensity of farming and forestry methods, and in climate between the member states. The economic viability of various biomass resources is heavily dependent on fossil fuel prices and availability; e.g. the fall in oil prices over the last 3 years has already caused some renewable energy companies to cease trading, and has resulted in less government concern about short-term and also basic energy research. At present, there are only two approaches which can result in a significant generation of renewable energy from biomass in Europe. The first is the production of combustible fuel and the second is the manufacture of ethanol of agricultural origin for use as a cosolvent in gasoline. At current fossil fuel prices, neither option is economic, unless some other factor such as waste disposal or pollution abatement, which effectively reduces the cost, can also be taken into account.(5). Utilization of wastes and residues is however usually economic, e.g. in the UK situation more than 16M dry tonnes is considered economically viable today.

It is estimated that over 300M tonnes of crop residues and over 230M tonnes of green residues and animal wastes are produced each year in Europe which can be used for energy purposes in the future. The potential resources in the 29 European FAO member countries for the direct combustion of agricultural residues are in the range of 30M toe (tonnes oil equivalent) and for biogas production some 20M toe. Apart from the 25M toe of fuelwood which is used in Europe, more than 22M toe of forestry residues and some 17M toe of wood processing residues can be used for energy purposes. Among the agricultural residues, straw is the most important resource with a potential of some 21M toe. At present some 17M toe of fuelwood and 2.5M toe of forestry and wood processing residues are used in direct combustion mostly in Scandinavian countries (official statistics). The Europe wide figure is probably twice this amount.

The estimated potential of liquid biofuel production in Europe varies from 20M to 100M toe, depending on the amount of available surplus products and crop residues and considering the extent of marginal and other lands which could be utilized for ethanol or plant oil production.(6).

The Use of Biomass in the EEC

Biomass, and particulary residues from forestry and the agriculture and food industries, is widely seen as one of the most promising alternatives for the substitution of fossil fuels in the EEC. Bioenergy production and exploitation could have an important role to play in modern European society. The biomass energy potential could be increased threefold by changes in agricultural or forestry procedures which would lead to an increased yields of wood, the use of catch crops and eventually energy plantations without requiring significant changes in land use.

At present biomass contributes 2% to 4% of the EEC's primery energy demand, including municipal solid wastes, amounting to about 20 to 40M toe (table 2).(7-8). Biomass is mainly in the form of residues firewood and charcoal; woody biomass provides about 60% of the industrial timber needs. Beyond the year 2000 biomass, with its minimum potential of around 500M tonnes dry matter per year, could provide the EEC with a cost effective , sustainable and environmentally acceptable alternative energy source. This could mean a contribution of 10% of the EEC's needs, equal to 100M toe per year, in addition to 120-230M m3/year of industrial timber making the EEC self-sufficient in timber. (8).

There are a wide range of locally available wastes and residues of potential value: forest residues, agricultural residues, and animal manures. Some of the agricultural and forestry products are used (e.g. furniture, boards, paper, etc). Within the EEC it is estimated that there are 320-400M tonnes per year of solid wastes equal to about 65M toe year. The estimated potential energy production by means of biogas technologies in the EEC is approximately 84M toe per year which can be achieved by the digestion of wastes and manure.(9).

Large-scale exploitation of biomass presents a number of important additional advantages, a potential employment impact of 500,000 new jobs; and improvement of the environment.

At present very few crops grown in the EEC are put to non-food/ non-feed uses. Some incentives to use surplus sugar and starch in industry alraedy exist. The short-term prospect for increasing outlets of cereals and sugar into non-food uses through the starch and chemical industries and fuel uses seem to be modest. This is despite the fact that research in recent years has identified a wide range of crops that have a potential to substitute for those currently in surplus and which could be put to other alternative uses. These include: fibre crops (flax, cotton); oilseed crops (oilseed rape, sunflower, euphorbia, etc); pulses (dried peas, soya beans, etc.);flavour, perfumery, medical plants (jojoba, peppermint, etc); energy crops (in addition to the conventional carbohydrate crops, Jerusalem artichoke, sweet sorghum, etc.) (10). Bio-ethanol has been at the centre of the political argument about the merits of putting agricultural produce to non-food uses. The EEC finds itself with a structural surplus of alcohol from wine production and it is estimated that by 1992 this surplus will reach around 2.2x10/9 litres. The potential market for ethanol fuel (based on a projected gasoline demand of 95M tonnes) is about 2.5M tonnes, this is equivalent to about

3.1x10/9 litres of ethanol (11). Many studies have concluded, however that although technically possible, there are no economic justifications for an ethanol fuel programme, at least in the short term. The EEC Commission noted that:
"bioethanol production calls for very costly investment in industrial plant. It is a policy, which once adopted, could well generate a lot of momentum and, therefore a permanent and growing burden(...) Nevertheless, to prevent the Community price level from stifling the development of new outlets, provision could be made for granting a marketing subsidy for bioethanol; this would at all times be equal to the amount of the export refund for cereals"(12).

Despite the economic argument against setting up a fuel ethanol industry assured of public subsidy there exists sufficient pressure in some member states contrary to the views of the Commission, that must be taken into account. As Willer puts it, "if ethanol, in the 1990s, were twice as expensive as premium petrol and if surplus grain could only be sold on world markets with the help of export restitutions of 104 to 125 ECUs per tonnes- this is 70% of the value of the product- as it was the case in 1988, it would be reasonable from both budgetary and general economic points of view to start building efficient ethanol plants" (13). Thus if ethanol may not seem to be a short-term option in the EEC, the door must be kept open so that the EEC remain in a position to exploit the ethanol opportunity when it becomes politically and economically viable. **(table 3).**

The Contribution of Forest Biomass .

Forestry is the favourite alternative land use system. Forests are the climax vegetation for most of Europe and in general trees of one species or another grow well in all environments. The prospects for developments in the use of forest biomass for energy lie in the use of coppice plantations and the establishment of short rotation forest biomass (SRF) plantations (tables 4, 5). A recent tudy (14) has demonstrated a number of important factors which will determine the future of short rotation biomass plantations in the EEC, namely:
a) technical feasibility. No longer in doubt having been tested and demonstrated for a variety of species over a considerable range of sites, although there still exists much scope for improvement.
b) availability of suitable land. It is now estimated that between 11 and 16M ha. will have to be taken out of food production over the next 15-20 years if agricultural surpluses are to be eliminated. In addition,a few million hectares which have already been abandoned could also be partly used for forestry plantations.
c) economic viability. This has also been demonstrated by the profitable Eucalyptus pulpwood plantations in Portugal and Spain, yielding 8% or more in real terms on the capital invested. In other parts of the EEC other types of trees could be used e.g. willows, poplars, etc.(table 5). Very divergent estimates of the productivity of forest biomass plantations have been made. Most available evidence indicates that realistic expectations in Europe are of the order of 8-12 tonnes harvestable dry weight per hectare per year.
d) markets. It is being increasingly recognized by politicians that forest biomass offers a major new market opportunity, with associated reductions in conventional arable crop output and environmental benefits. A major constraint so far has been the absence of a large scale market, and the lack of cash flow for the initial 4-5 years. Once a major market is established and supplies of forestry biomass (e.g. woodchips to generate electricity), are assured other outlets should develop, e.g. cattle feed, derivatives for industrial uses, etc. (15). Consumption of woodfuel in the home has also been greatly stimulated by the efficient new stoves which have been developed in recent years. Consumption of woodfuel within the EEC amounts to 23.6M m3 or about 20% of total forestry removals. (16)
e) Farmers attitudes. These are favourably changing with the introduction of a 'Set Aside' scheme for which, e.g in the U.K. short rotation coppice qualifies for £160 per hectare per year during a initial 5 year period.
f) Environmental impacts. This is a growing concern in the EEC and forestry plantations bring many positive environmental efects.
g) Political support. Increasing because of the chronic problems of food surpluses, the huge financial cost and the employment opportunities for less skilled workers.
Currently the EEC is only 56% self-sufficient in the supply of wood products. The main products of shortfall are sawnwood, pulp, paper and board with a self-sufficiency of 43% in paper and board products. The predicted growth in the market for paper and paperboard to the year 2000 would need an additional 42.2M m3. (15), which could be provided from forestry on about 3M hectares.

Sweden.

Within the European context Sweden is a particulary interesting case for its commitment to renewable energy. The growing public opposition to nuclear power resulted in the decision in 1980 to phase out nuclear power by the year 2010 and this has given a great impetus to renewable energy systems. It has been estimated that with efficient end-use technology, it would be feasible to move largely or even entirely to dependence on domestically produced renewable energy sources without running into serious land use or other environmental constraints. Presently about 13% of Sweden's primary energy comes from all form of biomass. Estimates put the possible contribution of biomass for the 2010-2020 decade between 275 and 655 PJ. Wood biomass contribution alone in 1986 was equivalent to about 7% of the total primary energy consumption (108 PJ).
The amount of marketable timber cut every year is about 70M m3 solid wood: an estimated 50M m3

of potential fuelwood is discarded during logging, of which between 11-28M m3 is considered economically recoverable. The Swedish government continues to give grants to help develop bioenergy combustion; the total R&D spending on biofuels is around Krone 12M annually. Research into energy crops has concentrated on SRF; the aim is to plant 10,000 to 20,000 ha. per year beginning in 1990 until the year 2000 and thereafter between 100,000 and 200,000 hectares annually. The most promising trees for SRF in Sweden are willow (Salix), alders (Alnus) and poplars (Populus). Good results have been obtained from high-yielding clones with the apllication of fertilizers. Some plots yielded up to 20 tonnes dry matter per hectare per year with estimated production costs comparable to oil prices.(5).

R.D & D Programmes.

Many techniques are available for energy production from biomass and are being actively improved in the EEC. The current R&D programme "Energy from Biomass" of the EC, with a budget of 20M ECU for the period 1985-88, is aimed at the development and recovery of biomass for energy purposes and the development of biological and thermochemical conversion technologies. The emphasis of biological conversion is in the production of biogas and the fundamental aspects associated with the use of yeasts, bacteria, enzymes, etc. A second sector of biological conversion activity concerns alcohol fermentation (e.g. the production of ethanol by Zymomonas mobilis and the improvement of ethanol production from xylose, novel alcohol separation processes, etc.). R&D on thermal biomass conversion includes pyrolysis (liquid fuels, charcoal, and gas) gasification, and direct liquefaction. (17).

The Joint Opportunities for Unconventional or Long-term Energy Supply (JOULE) is an EEC programme to be implemented in 1989-1992, at a cost of 39.3M, as part of its continuing support of R&D work in the area of non-nuclear and rational sources of energy. An important requirement is that the biomass R&D projects must be relevant to agriculture. The previous areas of research mentioned will continue to receive support with much greater emphasis on pollution control.(18).

The new Energy Demonstration Programme of the EEC (1989) requires that projects in this sector must take account of environment protection problems and fall into one of the following categories: a) Projects making an innovative direct use of plant, animal, urban or industrial waste or plants specially grown for energy purposes; b) Projects demonstrating innovative techniques for converting biomass and waste into derived fuels or chemicals or biochemical products, and projects involving an innovative use of such derived products.(19).

The Large European Bio-Energy Project (L.E.B.E.N) is also a proposed EEC financially supported project to be implemented by 1995 in the Arruzzo Region of southern Italy and 3 others are being considered. The object of the LEBEN project is the development of the agricultural and agro-industrial sectors of inner districts of the region through an integrated programme of massive exploitation of local renewable energy sources, particulary biomass. (20).

In addition, the European Cooperative Network on Rural Energy (CNRE) covers all aspects of renewable energy in Europe (covering over 200 scientitic institutions from 25 countries) facilitates information exchange, analyses national programmes and needs, fosters some R&D, and provides demostration of practical results. The International Energy Agency (IEA) of which there are 11 signatories, covers all aspects of SRF, the production, harvesting preparation and conversion of all forms of biomass energy.(5).

ENVIRONMENTAL FACTORS.

There seems little doubt that energy use is now changing the earth's climate- and with it many of the natural systems on which humanity depends. Emitting less CO_2 to the atmosphere requires using less fossil fuels, which implies that more efficient use of energy must be made and that other energy sources must be found to run the global economy.

The CO_2 concentration has risen 27% over the last century and reached the highest concentrations experienced on earth in the past 160,000 years. Humanity added 5.5. G t of carbon to the atmosphere in 1988 through fossil fuel combustion and another 0.4-2.5 G t through deforestation. If recent worldwide consumption growth rates of about 3% per year continue, fossil fuels could contribute 10 G t of new carbon annually in the year 2010. The global average temperature in the 1890s was 14.5 oC and by the 1980s it has climbed to 15.2 oC. (21). It is still argued by some that climate change will have positive as well as negative effects, and that it is a problem with which societies can readily cope. But this does not sufficiently recognizes the problems of the rates of change that are now projected, and the difficulty of adjusting quickly enough.

There are essentially three ways to displace fossil fuels: improving energy efficiency, thereby accomplishing the same tasks using less fossil fuels; developing renewable sources of energy; and expanding the use of nuclear power. Thus "the simultaneous pursuit of renewables and efficiency- and the abandonment of the nuclear power option- is the only way and cost-effective way to slow global warning" (21). It is an issue which goes behond the scope of this paper, but suffice it to say that despite the fact that nuclear power provides about 15% of the world's electricity and could reduce carbon emissions by replacing coal-fired power plants, it is a problem-ridden technology. Energy efficiency, in contrast, can have a larger, more immediate and cost effective impact on carbon emissions, e.g. energy efficiency improvements worldwide between 1990 to 2010 could reduce by 3 G t in the annual amount of CO_2 being emmited to the atmosphere.

Renewable energies can play an important role in reducing pollution, particulary biomass for energy. Though estimates vary, deforestation probably released a fifth to half as much CO_2 in 1987 as the burning of fossil fuel (21, 22). A major global reforestation effort is a possible strategy to preserve and expand the world's forests, and to slow the pace of climatic change. As trees grow, they remove CO_2 from the atmosphere thereby slowing the CO_2 build-up. Collectively, a global strategy of halving tropical deforestation and planting the equivalent of 130M ha. of trees in developing countries and 40M ha. in industrial ones could reduce worldwide carbon emissions from all human activites by about a fourth of current levels.(21). Myers estimates that to remove and store 3 G.t.of CO_2 from the atmosphere using tropical forest trees (asuming a productivity of 15-25 t of biomass ha./year) would require the planting of 300M ha./year.(23); while Marland's calculations are taht to remove 5 G t of CO_2 (based on a productivity of 7.5 tonnes/ha. (23); would require planting 700M ha.·(24). The CO_2 thus stored in the trees would be sequestered carbon for the lifetime of the trees possibly 20-60 years. The fate of the carbon thereafter depends on many storage and use options.

The sustainable production and conversion of plants and plant residues into fuels offers, therefore, significant potential for alleviating the pressure on forests and woodlands for fuel. These pressures have been significant threats to forest and tree resources, wetlands, watershed and upland ecosystems, etc. Biomass fuels make no net contribution to atmospheric CO_2 and can thus be regarded as a practical approach to environmental protection and longer term issues such as revegetation, acid rain and global warning.

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Table 1: Global Distribution of Energy Use, 1987.

	Developed Countries			Developing Countries			World Total		
	EJ	Mtoe	%	EJ	Mtoe	%	EJ	Mtoe	%
Oil	97	2211	37	32	730	23	129	2941	32
Coal	66	1502	25	39	884	28	105	2386	26
Gas	59	1333	23	10	222	7	69	1555	17
Biomass*	7	160	3	48	1088	35	55	1247	14
Hydro	16	355	6	7	169	6	23	524	6
Nuclear	17	377	6	1	27	1	18	404	5
Total	262	5947	100	137	3120	100	399	9067	100
Percent Total Energy	(66%)			(34%)			(100%)		
Population (billion)	1.2 (30%)			3.8 (70%)			5.0 (100%)		
Average Energy Use per Capita	218 GJ 4.96 toe			36.08 GJ 0.82 toe			79.80 GJ 1.81 toe		

Notes:
1.0 EJ = 10x10^18 J (approx. equals 1 Quad(USA)=quadrillion BTU)
1 Mtoe (million tonnes oil equivalent) = 44x10^6 GJ (44x10^15 J)
1 Mtce (million tonnes coal equivalent) = 29x10^6 GJ (10^15 J)
1 t air-dry biomass = 15 GJ
1 t wood fuel = 1.4 m3 wood
1 t charcoal is derived from 6-12 t wood.
* Biomass includes wood fuel, charcoal, agricultural wastes, dung, bio-ethanol and other forms of biomass energy.

Source: Scurlock J M O. and Hall D O, Biomass (1989.in press).

Table 2: Biomass Energy Potential in the EC-12 (Mtoe)

Agricultural wastes and residues (recoverable potential)	26.7(a)
Forestry, timber, indust. residues (available potential)	20.3(a)
Municipal solid waste	18.0(b)
Sewage	1.8(c)
Firewood	6.6(c)
Energy Forestry	28.1(c)
Catch crops	8.5(c)
Total	110.0

Note: Surplus foods could theoretically be used to produce about 20-25 Mtoe if all was converted to energy.

Sources: (a) OECD (1987) Renewable Sources of Energy. (OECD, Paris, tables 25, 26.; (b) Ref. 7; (c) Ref. 5.

Table 3 Present Use and Medium Term Land Use Potential for Bioethanol and Industrial Raw Materials in the EEC.

	Industrial Uses Present (1980/85) t.	Industrial Uses Future (2000) t.	Land Equivalent Present (1980/85) ha.	Land Equivalent Future (2000) ha.
Industrial raw materials.				
Oils and fats	1,175000	2,002000	1,107283	1,970472
Sugar	74000	140000	11273	82262
Starch	1,680000	2,944000(a)	414950	608000
		3,604000(b)		930000
Flax			60000	163650(c)
				272370(d)
Total of industrial raw materials (a+c)			1,593506	2,824384
(b+d)				3,255104
Ethanol	1,250000(e)			455370
	2,500000(f)			910740
Total of ethanol & industrial raw materials (a+c+e)			1,593506	3,279754
(b+d+f)				4,165844

Notes: a+b = two estimates of the future use of ethanol
c+d = two estimates of future demand for textile fibres
e+f = two estimates of future market penetration for ethanol as a fuel additive.

Source: Ref #9.

Table 4 Area of Short-Rotation Forestry in Some EEC Countries.

System	Area (ha)
Traditional system	9,106,100(a)
Pulpwood production	1,171,500(b)
Trials	817(c)

Notes: (a) Denmark, Spain, Greece, France, Italy (on rotations of 20-35 years); (b) Spain, Greece, Italy, Portugal (on rotations of 10-16 years); (c) Belgium, Germany, Spain, Greece, France, UK. (on rotations of less than 10 years).

Source: Based on Ref. 14, table 1.

Table 5 Area of Woodland in the EC as a proportion of total land area and as a proportion of the presently utilized agricultural area, 1985.

Country	Wooded area (kha)	% Total area	%Utilized Agricultural area.
Belgium	613	20	43
Denmark	483	11	17
Germany	7,328	29	61
Spain	15,543	31	57
Greece	2,262	17	24
France	14,606	27	46
Ireland	324	5	6
Italy	6,076	20	34
Luxembourg	82	32	64
Netherlands	293	8	14
Portugal	2,968	32	68
UK	2,266	9	12
Total EC.	52,040	20	37

Source: Ref. 19

FOREST FIBRE AS BIOENERGY

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There are enormous volumes of forest biomass which are theoretically available for energy production in Canada. Given the harsh constraints of the market place, however, it is unlikely that the 6 per cent share of energy now derived from biomass will rise as high as 8 per cent in the foreseeable future. In addition, environmental questions are being raised about nutrient losses through biomass harvesting, and the impact of intensive harvesting could also impact negatively on the subsequent productivity of forest soils. In spite of these cautions, it would be prudent to re-work the analysis at this time of uncertainty regarding hydrocarbon costs.

INTRODUCTION

The recurring crises over energy supplies have been underscored dramatically with the recent oil spill in Alaska. It took only a few days after the Exxon Valdez disaster one month ago for MacKenzie Valley pipeline proposals to resurface here in Canada. In other parts of the world we see nuclear power stations shutting down or simply removed from energy planning options. In Sweden, for example, they are expecting to use forest biomass to offset some of the power loss from shutting down nuclear generators.

It is in this volatile context that the present bioenergy seminar has been convened. The objective of this paper is to explore the potential role of forest fibre as a Canadian energy source. Some historic patterns of wood utilization will be given first, after which the discussion will turn to the outlook for both industrial wood availability and the prospects for using wood fibre for energy.

HISTORIC PATTERNS

Records of timber use in Canada are not well documented prior to the opening of this century, although we know that early colonists depended primarily on wood for domestic and industrial fuel. Wood was displaced in turn by coal and then by petroleum products.

A comparison of the total roundwood harvest and the fuelwood portion is shown for selected years in Table 1. The share of roundwood production used for fuel was 38 per cent in 1922, the first year for which consistent data are available. By 1950 the share had dropped to 13.4 per cent but the volume was still at a respectable 11.5 million m^3. Thereafter the share fell steadily to a minimum of 2.4 per cent in 1973. Then the OPEC petroleum crisis halted the downward trend and the fuelwood share is now around 4 per cent of the total roundwood harvest.

What is not shown in Table 1 is the use of bark, sawdust and other wood waste as fuel in the forest industry's manufacturing plants. In addition, the recovery boilers in kraft pulp mills burn lignin residues which are a by-product of chemical processes used to make wood pulp.

Table 1
Roundwood Harvest in Canada
and Fuelwood Use for Selected Years

	Total	Fuelwood	% Fuel
	(million m^3)		
1922	53.1	20.2	38.0
30	70.2	23.1	32.9
40	75.5	20.0	26.5
50	85.6	11.5	13.4
60	93.3	6.8	7.3
70	121.4	4.1	3.4
1971	119.7	3.7	3.1
72	124.1	3.4	2.7
73	143.8	3.5	2.4
74	137.9	3.5	2.5
75	115.3	3.8	3.3
1980	155.4	4.7	3.0
81	144.6	5.5	3.8
82	127.0	5.7	4.5
83	156.9	6.2	4.0
84	167.5	6.6	3.9
85	168.7	6.7	4.0
86	177.1	6.8	3.6

Source: Statistics Canada

Also of historical interest is the breakdown of fuelwood into hardwood and softwood species. Systematic data were not collected prior to 1970. In that year hardwoods accounted for nearly two thirds of the total fuelwood used and this share has now risen to three quarters. It should also be noted that fuelwood data are based on crude estimates that may not accurately reflect the amount of wood consumed outside the money economy. Even if we throw in 2 million m^3 more on this account, the fuelwood share does not reach 5 per cent.

OUTLOOK FOR INDUSTRIAL TIMBER

It was not long ago that most Canadians thought we had an inexhaustible forest, that it was much less expensive to deliver to mills than was the case for our competitors, and that the world's customers would always beat a path to our door. This kind of complacency has now vanished.

Experience has now shown that our lumber producers are not immune to sawlog deficits. Shortages have shut down quite a number of mills across Canada since 1980, and others face a similar threat in the decades just ahead.

How can we explain this abrupt change in perception from timber abundance to threatened curtailment? There are several reasons which can be summarized quickly. First, the harvest of softwood logs in Canada was approximately 175 million m^3 in 1987. In 1986, the aggregate provincial annual allowable cut (AAC) of softwood was estimated to be 166 million m^3 (Reed), and it does not appear that the AAC has increased since then. In other words, the total industry harvest has technically exceeded the combined AAC, for the first time, and additions to manufacturing capacity between 1987 and 1992 will require perhaps another 10 million m^3 of softwood fibre.

Second, forest regeneration success rates after logging have fallen below expectations, with the result that annual allowable harvests are probably over-estimated. Only 70 per cent of the areas planted to spruce and pine in the mid 1980's are expected to become satisfactorily stocked without re-treatment. In the case of naturally regenerated sites, according to Kuhnke (1989), only 50 per cent success rates are expected. This means that the next crop will be delayed and will probably be smaller than that hoped for by provincial forest services.

Meanwhile, a third factor has arisen. The mature forest has been shrinking steadily due to planned harvesting, but on a pre-determined schedule which was calculated to coincide with the availability of new plantation timber. However, we are now experiencing the unplanned application of environmental guidelines, and the more recent pattern of setting aside large areas for recreation, wilderness, wildlife habitat and other single use categories. The current demands for reservation of old growth, such as the Temagami area in Ontario and South Moresby in British Columbia, are just two episodes in a lengthening progression of unplanned encroachments on forest licenses. This practice reduces the volume of old growth that was counted on in the period before the next crop is ready for harvest.

Fourth, losses of mature timber to insects and wild fire have been more severe than anticipated when the annual allowable cut calculations were made a decade or more ago. A further shrinkage of the available supply became apparent when forest inventories were evaluated for economic accessibility. Accordingly, it means little to a forest industry firm competing internationally to be told by the provincial forest service that there is plenty of unoccupied timber out there, if it is 500 km from the mill or is largely unmerchantable for reasons of quality, species mix and product suitability. This can be particularly frustrating when obvious opportunity is recognized in expanding markets. Every study of forest product consumption trends points to a buoyant outlook, in volume if not in price, in the next couple of decades.

The foregoing account can be summed up in the accompanying Table 2 showing softwood timber supply relationships in Canada. Even if the mills could count on the annual allowable cut as presently determined, which is not the case in British Columbia and perhaps in other regions, the industry capacity to use wood fibre is now increasing well beyond the AAC.

Table 2
Softwood Timber Supply Relationships in Canada in 1987

Annual allowable cut (AAC)	166 million m^3
Harvest estimate	175
Industry capacity (est.)	190

It should be noted that the level of forest management and protection has a great deal to do with future timber availability. However, even by doubling the number of seedlings planted since 1980, we do not appear to be offsetting regeneration deficiencies, losses to insects, and timber lands set aside for wilderness and recreation purposes. Moreover, the spending on plantation maintenance is still inadequate to ensure a robust second growth. Optimism does not seem warranted for industrial softwood timber, given present forestry budgets.

In contrast to the rather unpromising softwood situation just described, hardwood availability is presently well above the industry capacity to use it or the market's readiness to accept more hardwood products. Going back to 1970 we find 6.8 per cent of industrial roundwood output in hardwood species. By 1986 this share had fallen to 6.0 per cent. There is, however, a marked increase in hardwood utilization at the present time, especially in Alberta. New capacity is being built to use hardwoods in pulp and paper. The gap between hardwood availability and use is expected to narrow as a result. The hardwood AAC is roughly 38 million m^3, which is three times the current harvest level.

FOREST BIOMASS POTENTIAL

A great deal of research has been directed to the bioenergy potential of forest lands in the years since the oil emergency in the mid 1970's. Interest is now rising sharply again and earlier studies are being re-examined. The approach taken here is to draw on several existing reports for insights into the current energy supply profile and the likely role of wood in the future.

The Canadian energy supply picture is summarized in Table 3 for the years 1976 and 1986. The "off oil" policy obviously worked as intended, as shown by the sharp drop from 51 per cent to 36 per cent. Biomass increased from 4 per cent to 6 per cent in the decade shown.

The unit of measure used here is the exajoule (EJ), which can be related easily to roundwood equivalent. The present industrial roundwood harvest of 190 million m^3 would produce about 1.3 EJ if the entire harvest were converted to energy.

Not counting industrial roundwood, forest biomass is generally classified into six separate categories. This was done by InterGroup Consulting Economists (1982) in an ENFOR study for the Department of Energy, Mines and Resources. It has been a standard reference since that time. The categories are shown in Table 4 in oven dry tonnes

(ODt) for the base year, 1990 and 2000.

Table 3
Canadian Energy Supply Profile
1976 and 1986

	1976		1986	
	EJ	Per Cent	EJ	Per Cent
Coal	0.67	9	0.98	11
Oil	3.70	51	3.04	36
Natural gas	1.69	24	2.22	26
Hydroelectricity	0.72	10	1.02	12
Nuclear	0.16	2	0.80	9
Biomass	0.30	4	0.54	6
	7.24	100	8.61	100

Source: National Energy Board

Table 4
Estimated Forest Biomass Supply
in Canada's Provinces
(million ODt)

	1980	1990	2000
1. Surplus merchantable timber	33.3	28.8	25.1
2. Mill residues	15.8	17.3	19.1
3. Logging residues	24.1	26.8	29.9
4. Salvage of unmerchantable	27.8	27.8	27.8
5. Stand conversion	10.8	10.8	10.8
6. Energy plantations	-	2.0	7.9
	111.8	113.5	120.6

The provincial shares estimated by InterGroup showed British Columbia, Ontario and Quebec with 24, 25 and 24 per cent respectively and this pattern did not change appreciably in the three years given in Table 4.

The energy values in these tonnages were converted by InterGroup to crude oil equivalent. Thus, 111.8 million ODt of forest biomass in 1980 were estimated to equal 950,000 barrels per day of crude oil. With this broad picture in mind we turn next to a brief analysis of each category in Table 4.

1. Surplus merchantable timber. This is calculated as the difference between the AAC and the harvest of industrial wood. The aggregate AAC has been reduced by about one fifth since the Inter Group estimates were made. Meanwhile the annual softwood harvest has risen sharply and to a point slightly above the combined AAC for the 10 provinces. There is still a theoretical surplus of merchantable hardwoods. On balance, the surplus is probably not more than 6 million ODt today, nearly all of it hardwood species, and this amount will fall to a negligible figure in another decade.

2. Mill residues. Sawmills, plywood plants and other solid wood manufacturing firms turn out sawdust, shavings, bark and other by-products. In the past decade, substantial efficiencies have been achieved in these operations to increase the lumber and veneer recovery factors. This has been achieved through narrower saw kerfs, improved sawing and peeling technology, end glueing, and even the use of limited amounts of sawdust and shavings in the pulping process. A growing volume of residue is used as well in wood based panels. Equally important is the phasing out of beehive waste burners in favor of power boiler consumption of bark and other lower grade residues. Co-generation of electric power for sale to public utilities is increasingly common. So within little more than a decade, the surplus of this material has fallen considerably. The volume of mill residue which is still used as land fill or burned as waste is now relatively insignificant. What appeared to InterGroup as a firm 17-19 million ODt has fallen to perhaps 4 million ODt.

3. Logging residues. Likewise, logging residue volumes are not as promising as was thought to be the case earlier. Closer utilization is being practiced in logging operations, both to improve the visual image of a clearcut and to secure more roundwood in areas where fibre deficits might otherwise be anticipated. Moreover, as the forest industry moves progressively into second growth plantations, there will be less waste and breakage left behind after logging. More importantly, industry will undoubtedly mount a major effort to recover commercial thinnings, a fibre supply option which our competitors have been using for a considerable time. So by the year 2000 we will see a further drop in availability of logging residues as industry moves to supplement conventional pulpwood supplies.

Another consideration affecting logging residues will be the increased awareness of the importance of these materials for nutrient recycling. In addition, Standish (1988) has pointed out that intensive harvesting and relogging for residues may reduce the productivity of future crops by altering soil properties such as density, aeration, water retention, siltation and general erosion.

The warning put forward by Kimmins in 1977 and subsequently is even stronger. Speaking of nutrient losses he makes this point:

> "The advent of fibre farming (total utilization of tree crops grown on short rotations) raises the spectre of soil impoverishment on many forest sites."

Even small negative impacts may tip the scales on those relatively fragile sites where logging is already in question. As nutrient problems and soil disturbance become better understood, we may very well see a move to lessen the collection of logging residues. By the year 2000 the available logging residues will likely be well under 20 million ODt, rather than the 29.9 million suggested earlier by InterGroup.

4. Salvage of unmerchantable timber. At the present time some stands are simply by-passed because the timber is rendered unattractive for reasons of species mix, excessive decay, high cost, small diameters and difficult access. The volume of such standing timber may be equal to logging residues, according to InterGroup. In reality the costs of recovering this will be relatively high.

5. Stand conversion. In all forest regions of Canada there are large stands which are not going to be commercial within a reasonable time, but they encumber good growing sites. This is often the case for example, with mixed hardwoods which have followed a clearcut of softwoods, with brushy sites which have failed to regenerate satisfactorily, or with forests killed by insects or fire. Land managers like to see these productive sites converted back into commercial crops for future generations. Where the costs of this conversion can be shared between the silviculturist and the energy producer, feasibility might well be established.

6. Energy plantations. Ontario researched the potential for short rotation poplar plantations very thoroughly, both for pulpwood and energy. While this possibility looked more promising a decade ago than it does today, the outlook could change quickly if energy prices spiral sharply higher once again.

Another useful reference on forest biomass is by Bonnor (1985), although his estimates cover fewer categories than InterGroup did and there are no projections. Bonnor does state that there is enough physical biomass to supply one quarter of Canada's energy requirements on a sustained basis. However, he scales this down to a more realistic level, suggesting that Canada could double the present share of energy now supplied from forest biomass. Bonnor includes in his estimate only the unused mill residues, logging residues and non-commercial trees and stands. He appears to exclude the present surplus of merchantable roundwood, stand conversion and energy plantation potential.

In short, the physical potential of energy biomass has been amply demonstrated. Even though, in my view, the physical volumes available in the year 2000 or 2010 will not be nearly as promising as InterGroup projected during a period of higher petroleum prices, there might still be perhaps 50-60 million ODt or more available for energy.

Another significant factor affecting forest biomass availability has arisen as part of the environmental movement. Wood-fired electric power plants have proven to be quite unpopular in the United States. According to Frankena (1989), opposition arises on several counts: fear of air pollution, concern over nutrient loss from biomass harvesting, alleged threats to water supplies, and the prospect of domestic fuelwood shortages. Two projects in Michigan were abandoned, along with one in California, and a second one in California proceeded with lesser difficulty. Public utilities are now very reluctant to propose such investments. Doubtless the same kind of opposition would arise in Canada, although smaller projects associated with local municipal facilities or established forest industry plants might still gain local consent.

COSTS OF FOREST BIOMASS

The critical determinant will of course be the cost of forest biomass relative to hydrocarbons or other types of energy. A clear indication of costs can be taken from previous studies. Overend (1980) remarked of biomass that "the cost per ton roadside is borderline or uneconomic". His suggestion was that biomass collection would have to utilize a technology quite different from conventional methods. Some attempts at this have already been made. Stora Forest Industries has operated mobile chippers in stands killed by the spruce budworm in Cape Breton, with apparent success. The chips produced by this method are hauled short distances for use in power boilers.

In another study, McDaniels and Manning (1987) examined biomass costs in seven different regions in B.C. As expected, the results show the great majority of mill residues can be delivered for very little. In contrast, logging residues, non-merchantable salvage and other types generally cost in excess of $60 per ODt. In the final analysis, biomass energy potential will be determined by economic accessibility, as is the case with industrial timber. Forest industry companies have learned to discount the physical volumes said to be available, on very practical grounds of delivered costs within a highly competitive market place. Bioenergy analysts must begin to do the same kind of scaling down of those volumes identified as being available in physical terms.

SUMMARY

It is difficult to feel as confident today as some of the earlier research projects indicated. Certainly it is timely to begin a thorough re-assessment of the bioenergy potential from Canada's forests. Meanwhile, the following observations are noted.

1. Whatever changes take place in biomass utilization will be slow and painful, inasmuch as environmental factors now play an overpowering role in public policy. Soil impacts and nutrient losses will be used to argue against wood-fired electricity generation. This aspect is perhaps the most serious caution for forest biomass proponents.

2. Technology may in fact advance to the point where forest biomass collection is a more attractive possibility. A quick look around the world, however, suggests that forest fibre is no better off in this respect than other types of energy can also claim. Reports on competing energy forms also speak of cost reductions via technology.

3. Foresters were prompted in the late 1970's to scale down annual allowable cuts of industrial roundwood because of economic accessibility constraints imposed in a competitive market place. It would be sensible to do the same with high cost forest biomass tonnages.

4. It seems likely that a flurry of new feasibility studies will be undertaken in the next few months. Until the results are in, we can only speculate. My judgement is that forest biomass will likely increase its 6 per cent share of Canada's energy by a percentage point or two at most.

Events in the energy field are once again moving at a fast pace. Nevertheless, new policies and programs must be advanced with caution. It is hoped that the perspective presented in this paper will help to set the stage for bioenergy discussions in the months to come.

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MUNICIPAL SOLID WASTE AS AN ENERGY SOURCE

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1.0 INTRODUCTION - MSW - "FEEDSTOCK"

1.1 Quantity

MSW is considered herein to exclude Hazardous Solid Wastes but to include Residential, Commercial and Industrial Solid Wastes. Some Industrial Solid Wastes are disposed of directly by the generating industry. Some companies have their own incinerators. For example: 3M (60 TPD), London; Ford, (70 TPD) Oakville; and General Motors Co. (70 TPD), Oshawa. Some waste is disposed of as useful materials to other industries through "waste exchanges". Other municipal wastes such as asphalt, concrete, scrap metals and clean fill have been recycled or disposed of historically without being measured as part of the traditional municipal "garbage"/"refuse"/"solid waste" disposal system.

It is established that Canadians generate over 20 million tonnes of MSW/year (and rising). Per capita generation rates range from less than 500 lbs/capita/year in rural areas to over 1T/capita/year in urban areas. Variations depend mainly on the type of industry in a community, affluence and stage of development (stable or rapid growth). Figure 1 shows some numbers from southern Ontario for current waste generation.

Figure 1

CURRENT GENERATION RATES, RECYCLING QUANTITIES AND RECYCLING TARGETS

Region	Current Waste Generation	Current Landfill Diversion	Projected Municipal Recycling Percentage 1989	1990
	Thousands of Tonnes/yr			
Durham	326	20	6.1	12.0
Halton	236	37	15.9	19.0
Peel	762	80	10.5	13.1
York	523	19	4.0	8.0
Metro	2500	156	6.3	12.5
	4347	312		

Provincial Guidelines: 25% Reduction by 1992
50% Reduction by 2000

1.2 Composition

Residential composition is still generally based on work done by Bird & Hale/Ontario Waste Management Advisory Board, 1980 (1) (2). Figures used in Peel are shown on Figure 2. These are being re-examined but, are generally representative. There is a general trend to an increasing percentage of plastic, aluminum and paper and a decrease in food wastes, glass and metal.

Figure 2

REGION OF PEEL WASTE COMPOSITION

Population Related Waste	Composition	1986 Tonnes Available for Disposal
Residential		
Municipal		
Public Waste		
Drop-off bins		
Non-profit recycling		
- Paper and cardboard	35.1	82,081
- Food wastes	22	51,594
- Yard wastes	15	35,178
- Glass	8	18,762
- Metals	8	18,762
- Plastic/rubber/leather	5	11,726
- Wood	3	7,035
- Cloth and misc. (other)	4	9,380
Farm Waste		804
Spill cleanup material		208
Operational support waste		737
SUBTOTAL		236,067
Employment Related Waste		
Industrial		
Commercial		
Institutional		
- Paper and cardboard	46.5	117,649
- Organics	10.0	25,301
- Glass	5.0	12,650
- Metals	7.2	18,216
- Plastic/rummer/leather	8.0	20,241
- Wood	2.0	5,060
- Misc. (other)	21.3	53,891
Construction		68,880
Transfer Station		768
Slag		5,466
Industrial Sludge		11,011
Grit/Screenings		1,055
Fly Ash		177
SUBTOTAL		340,367
TOTAL		576,433

Note: 1. Guidelines for Recovering Residential Waste Materials through Source Separation - Ontario Waste Management Advisory Board, July 1980.

Employment Related wastes vary with community and the industrial base. Figure 2 shows estimates for the Region of Peel. These are being refined by Regional inspectors' reports from regular inspections and liaison with industry. They may also change significantly with increases in tipping fees from $20/tonne of a few years ago to $90/tonne.

Approximately 70% of the wastes could be directed to incineration with a BTU value in the range of 4,500 BTU/lb (10.46 MJ/kg) which would be increased with the increase in plastics and paper.

1.3 Summary

The foregoing may seem a "bonanza" to energy buffs, but it is a "crisis" to the rest of the world.

2.0 MSW - DISPOSAL

2.1 Historical

Ancient dumps are "archaeological treasure chests". These were followed with "back-forty"/"old quarry" dumps with open burning and a varied animal life. There was little or no engineering or environmental input to this disposal method. Urban areas in the 1930's moved burning into mechanical incinerator facilities, generally without energy recovery (EFW). Air pollution was not out of place with general conditions at that time but subsequently led to many closures.

Larger dumps and early landfills were also less costly for disposal. The pollution potential was often hidden and may result in costly future clean-ups.

Research and trials with more sophisticated disposal methods developed in the 1960s including: sanitary landfills; EFW; composting; pyrolysis; hydropulping; mechanical sorting/recovery; refuse derived fuel (RDF); recycling etc.

1.2 Present

Emphasis now is strongly on reduction, re-use, recycling and recovery (4Rs). The fourth "R" including "energy" recovery. As this has fallen into disfavour in some quarters, we have been using "3Rs" to cover everything excluding EFW.

3.0 REDUCTION, RE-USE, RECYCLING AND RECOVERY (4RS)

Reduction is generally given first priority among the waste management options. Emphasis is to reduce quantities of waste, reduce the environmental impacts of other disposal methods, and to conserve natural resources. Standardization is required on definitions of achievements and targets quoted. For example:

- % of residential or total wastes?
- what is base tonnage? (If one picks one historical year, it is affected by changes in generation rate/reduction and it is difficult to measure or try to estimate all factors each year?)
- do they include EFW or RDF?
- what is the community size and type?

Do we base planning targets on proven technology or anticipate future developments for long term planning?

Further research is required on total environmental impacts of the 4Rs but there are obvious net benefits, such as:

- recycled paper reduces the number of trees required which are then available for other uses (19 trees/tonne newspaper recycled)[4]
- recycled glass, aluminum and metal reduces energy requirements in manufacture compared to use of raw materials only.

  For example:
  - 30% cullet gives 3.5% fuel savings
  - 85% cullet gives 17.3% fuel savings[3]
  - 3 barrels of oil/tonne of steel cans recycled
  - 70% less energy/tonne of aluminum recycled[4]

- recycled organics for compost production to improve soil capability
- reduced potential contamination from other disposal methods.

The projected impact of the 3Rs on wastes using proven technology for disposal in Peel Region is shown on Figure 3. These are low compared to Provincial objectives which have been stated recently as 25% reduction in wastes by 1992 and 50% by the year 2000 before incineration or landfilling. Details of how these greater "3Rs" targets may be accomplished are still being developed but include:

- reduction in packaging and other sources of waste (particularly industrial) which will require Federal as well as Provincial action
- re-use of an item again in its original form for the same or a different purpose
- recycling and composting to include recycled glass, metals and newspapers in the original manufacture; organic garbage composting to enrich soil; plastics to form plastic posts, etc.
- recovery by anaerobic digestion to produce methane gas; extraction from mixed waste of various classes of materials for recycling (which may be less marketable).

Although these objectives are sought by voluntary methods, several specific wastes such as cardboard, wallboard and tires have been banned for some landfills and mandatory recycling may be introduced through changes in Provincial and Municipal Regulations.

Recent approval by the Consolidated Hearing Board of a landfill site for the Region of Halton stipulated that the Region increase its 23% target

for the 3Rs and advance its plans for an EFW facility.

It is critical that; public commitments be enhanced; purchasing be geared to encourage the use of recycled material; and that markets be developed to use the materials. An overall analysis of net potential energy savings would be invaluable.

4.0 INCINERATION: "ENERGY-FROM-WASTE" (EFW)

In the early 1980's this disposal option was given strong, second-top priority for both mass burning and Refuse Derived Fuel (RDF).

It is now being relegated to a lower priority because of:

- public fear of air emissions (and ash disposal) despite extensive tests (NITEP) and advanced technology demonstrating that conservative guidelines can be readily met. Additional work is being done to provide analysis of long term risks for both the direct and indirect exposure to local residents from incinerator air emissions (5).

- this fear "fueled" by:
  - "NIMBY";
  - data from old incinerators;
  - advocates of 3Rs who claim that EFW will interfere with commitments to 3Rs. Evidence at the recent SNC Hearing in Brampton, Ontario for the proposed 360 T/day CONSUMAT facility demonstrated that there was more than enough garbage in Peel for all proven systems. Also the 3Rs program removal of both non-combustible and combustible materials did not significantly affect the BTU value of the MSW.
- postponement of the conventional fuels crisis
- Greenhouse effect

A June 1988 Wall Street Journal article (6) is frequently quoted as a basis for discontinuation (or at least for a moratorium) on EFW. It stated that in the USA, "new incinerators are proving far more expensive than many communities dreamed. Some have spent millions of dollars to cover debt costs after revenues from electricity sales failed to meet expectations... More than $3 billion in projects have been scrapped in the past 18 months, and new orders have slowed to a trickle..."

A November 1988 article in Waste Age, "Refuse to Energy is Not Dead"(7) confirmed that there has been a slow-down in EFW facilities, partially due to awaiting new regulations, and an increase in shutdowns for a variety of reasons, but also that the numbers continue to increase:

- operational; 63 in 1986 and 102 in 1988
- in conceptual stages of development; from 57 in 1986 to 139 in 1988.

Canadian installations include:

(a) Operating

- PEI Modular Incinerator (1982) - 100 T/day
- Montreal Von Roll, moving grate water wall incinerator (1970 - retrofitted 1985) - 120 T/day
- Quebec City Von Roll (1975 - upgraded in 1986) - 908T/day
- SWARU, Hamilton, RDF (1969 - retrofitted in 1984) - 450T/day
- Victoria Hospital, London, Modular Incin. (1987) - 270T/day
- Greater Vancouver Regional District, Mass Burning, (1988) - 750 T/day

(b) Consolidated Hearing Board Approval

- SNC, Modular, Peel Region, Ontario - 360 T/day

(c) Pending

- St. Lawrence Cement, Peal Region, RDF
- TRINTEK, Toronto, Multi-stage, Mass Burning - 400 T/day

(d) Closed

- Commissioners Street Incin., Tor. (1953 - upgraded 1974/75 - closed 1988)

New EFW plants will probably have to include upstream recycling, special ash handling provisions, BACT-EA level emission control, extensive fuel gas monitoring systems and will be more likely to produce electricity than process steam and electricity.

5.0 METHANE GAS FROM LANDFILL

Usable gas emissions from landfill result from the anaerobic bacterial degradation of organics and contain approximately 55% methane and 45% carbon dioxide with trace amounts of other gases.

The rate of production and composition of the gas is extremely variable (in the order of 1500 cf of gas/ton of waste), depending upon:

- composition of the MSW
- waste loading rate
- age of landfill
- moisture
- cover to limit infiltration of air

The problems associated with gas generation include:

- fire and explosion hazards on and off the site
- vegetation kill
- odours
- air pollution

In the past, the gas has been allowed to vent to the atmosphere. In 1984, the California Legislature passed Bill AB3525 (Calderon) setting forth gas and ambient air testing requirements at disposal sites in California (8).

A 1983 survey (9) of 75 landfill gas facilities in the USA showed:

- 29 operating (vs. 8 in 1980)
- 8 under construction. 35 in planning
- 3 shut down

B.I.O. Gas Industries, Vancouver (10) have been promoting the recovery of this resource at a landfill gas recovery facility in Richmond, B.C. The operation supplies gas to Canada Cement Lefarge, Richmond, B.C., with an energy equivalent of 100 barrels of oil/day (EMR funding assistance). Other Canadian initiatives include a small greenhouse heating system in St. Thomas, Ontario; and supply to a Concrete Pipe Manufacturer in Kitchener, Ontario.

Gas is usually classified as:

(a) "Medium" BTU gas-(500-600 BTU/cf: 15-18 MJm-3), which is generally "raw" gas and is used to drive turbines, generate steam for space heating/electricity, in cement kilns, etc.

(b) "High" BTU gas-(900-1000 BTU/cf: 27-30 MJm-3), which is raw gas treated to remove moisture, carbon dioxide, other contaminants, and particulates and can then be incorporated with "pipeline" gas. Treatment is expensive and has to be weighed against the market situation.

The emphasis on reduction of organics to landfill could have a significant effect on this energy source in future landfills.

SUMMARY

At the present time MSW represents a significant potential source of energy directly recoverable through Energy-From-Waste plants, Refuse Derived Fuel preparation or as methane gas from organic waste digestors and landfills.

The Provincial leadership in Reduction, Re-use, Recycling and Recovery is having a significant impact on these options with the emphasis on savings in energy from reduction in packaging materials and the re-use of recycled materials rather than direct energy recovery. New direct energy recovery systems will have to demonstrate that they do not interfere with the other 4R options.

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Figure 3

HISTORIC REVIEW/TARGETS FOR 3 RS PROGRAMS IN PEEL

		1986	1987	1988	1989	1993	2001	2015	2027
POPULATION									
RELATED	Tonnes	19,300	22,700	21,500	27,400	83,800	118,200	145,700	146,600
WASTE	%	6.8%	7.6%	6.6%	8.1%	25.7%	30.0%	30.0%	30.0%
EMPLOYMENT									
RELATED	Tonnes	13,800	13,200	37,300	87,500	88,200	124,500	156,600	161,400
WASTE	%	3.2%	3.0%	7.8%	17.8%	17.9%	21.0%	21.0%	21.0%
TOTAL	Tonnes	33,100	35,900	58,800	114,900	172,100	242,800	302,300	308,000
3RS PROGRAM	%	4.6%	4.9%	7.3%	13.9%	21.0%	25.0%	25.0%	25.0%

NOTE: FIGURES REPRESENT NEW RECYCLED MATERIALS AND DO NOT INCLUDE TONNAGES FOR MATERIALS ALREADY BEING RECYCLED PRIOR TO 1984, I.E., CONCRETE, ASPHALT, SEWAGE SLUDGE

CLIMATE CHANGE: IMPLICATIONS FOR ENERGY

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ABSTRACT

Scientific evidence clearly indicates that the concentrations of greenhouse gases in the atmosphere are increasing dramatically. Large global climate change due to these increases appears highly probable. International concern about the possible consequences is likely to lead to global action to control the emissions of greenhouse gases. Such action would have major implications for Canadian energy policies. These are briefly discussed.

INTRODUCTION

The current decade is likely to go down in history as the decade in which the World finally recognised that economic development and environmental protection are not contradictory objectives, but in fact inextricably linked. Sustained development demands a sustained resource base, particularly with respect to natural resources. One of the most important natural resources is the Earth's atmosphere, a limited resource that belongs to no one, yet touches everyone. The very existence of life on Earth depends upon sustaining the remarkable characteristics of the atmosphere. Yet, after several centuries of relentless and ever increasing emission of effluents into the atmosphere by an industrialized global society, there is now clear evidence that the atmosphere is changing. These changes are unprecedented in human history and may well be irreversible. The many environmental issues related to the atmosphere, particularly that pertaining to climate change, find their root causes in these fundamental changes.

Historically, the development of policies on the use of energy to fuel our industrial activities has paid scant attention to global environmental implications. The evidence that such policy developments in future are likely to be prime determinants in how much and how fast the global atmosphere will change clearly suggests that is no longer acceptable. Consideration of options that will help to control emissions and protect the atmosphere from their disruptive effects will be of utmost importance. Future international conventions and protocols may in fact compel nation to do so.

In this paper, the evidence for changes in the atmospheric concentrations of 'greenhouse' gases and the scientific basis for concern about related climatic change are summarized. Some of the recommendations of recent meetings on the issue are then reviewed, followed by a discussion of related implications for energy use.

EVIDENCE FOR CHANGE

Regular measurements of atmospheric concentrations of CO_2 were started at Mauna Loa, Hawaii, in 1957. They are now being recorded at numerous stations around the world. The results are irrefutable - the mean concentration of atmospheric CO_2, now at about 350 parts per million by volume (ppmv), has increased by 11% over the 30 year period (Rodhaine et al, 1988). When compared with information obtained from air bubbles fossilized within the Antarctic ice cap, it appears that current values are about 20-25% higher than the previous highest values during at least the past 160,000 years (Barnola et al, 1987).

The principal source of additional accumulation of CO_2 into the atmosphere appears to be the release of carbon as carbon dioxide during the combustion of fossil fuels. Currently this source causes the emission of about 5.5 billion tonnes of carbon into the atmosphere as CO_2 each year (Marland, 1989). In additional, the destruction of vast tracts of tropical timberland to make way for agricultural development appears to be contributing an additional 1-2 billion tonnes each year (Houghton et al, 1989). Although these releases are relatively small compared to the natural annual fluxes of carbon between atmosphere, biosphere and ocean (Trabalka, 1985), they represent a cumulative one-way release of carbon from long-term reservoirs into the atmosphere, causing an imbalance in the natural global carbon cycle.

Fortunately, not all of the unnatural emissions of carbon into the atmosphere remains there. The natural system appears able to accommodate a portion of these additions to the atmosphere by re-absorbing as much as 60% into other carbon reservoirs, primarily the oceans (Bolin et al, 1986). The progressive increase in atmospheric CO_2 concentrations is caused by the approximately 2.5 billion tonnes of carbon that remains in the atmosphere each year.

Other atmospheric constituents important to climate are also changing rapidly. Methane

concentrations, monitored since the early 1970's, are increasing at about 1.1% each year and are already more than double those of pre-industrial times (Khalil et al, 1987). Although increased global populations of cattle and acreage of rice paddies are believed to be primary sources, release of methane during coal and gas extraction processes and biomass burning are estimated to account for about 40% of the increase. Nitrous oxide is also increasing at 0.3%/year, with an estimated 50% contributed by fossil fuel combustion. Surface concentrations of ozone are rising in urban areas, largely as a by-product of energy use for transportation. Other gases such as chlorofluorocarbons, although as yet low in concentrations, are in many cases increasing very rapidly (Wuebbles and Edmonds, 1988).

Principal Greenhouse Gas	Concentrations (Parts per Billion)			Relative Efficiency Compared to CO_2	Man-Made Sources
	Present	Trend (%/yr)	Projected 2050 AD		
Carbon Dioxide (CO_2)	[illegible]	0.4	[illegible]	1	Burning of coal, oil and gas, deforestation
Methane (CH_4)	[illegible]	1.1	[illegible]	20	Biological activities related to increased human and farm global population
Nitrous oxide (N_2O)	301	0.3	370	200	Increased use of fertilizers, burning of coal, oil and gas
Chlorofluorocarbons					Industry
CFC 11	0.17	8.7	1.1	17000	
CFC 12	0.28	6.0	1.8	20000	
Tropospheric Ozone (O_3)	Variable	~1	~10.5%		Photochemical reaction of other gases

Table 1. Concentrations, trends, significance and sources of principal greenhouse gases (adapted from Bolin et al, 1986).

The above greenhouse gases have several common features (Table 1). They are all climatically important gases that already have an abundance sufficient to significantly influence the heat radiation balance of the climate system. They are all increasing in concentration due to human activities. Finally, most are increasing in concentration at least partly due to emissions from the extraction and combustion of fossil fuels.

BASIS FOR CONCERN

Greenhouse gases collectively behave as an insulating blanket around the planet. Their effect on the incoming solar heat energy which fuels the earth's climate system is minimal. However, their combined influence on the outgoing heat radiation, emitted from the earth's surface and lower atmosphere towards space to cool off the climate system, is large. By absorbing and returning much of this outgoing radiation, they effectively trap heat within the lower atmosphere. This "greenhouse effect" is naturally occurring and essential to life on earth. Without it, the earth's surface would be more than 30 degrees C colder.

Projections of future CO_2 emissions into the atmosphere clearly suggest at minimum an eventual doubling of atmosphere CO_2 concentrations over preindustrial levels. However, the timing of such doubling remains uncertain, since long-term future human behaviour with respect to energy consumption is largely unpredictable. Concentrations of other greenhouse gases are also likely to increase significantly in future decades, adding to the climatic effects of rising CO_2 levels. A combined effect on climate equivalent to a doubling of CO_2 appears possible as early as 2030 AD, and highly probable by 2050 AD (Bolin et al, 1986).

Atmospheric modellers do not as yet agree on the magnitude of the net climatic changes that would result from an enhanced greenhouse effect. Nor do they agree on the regional characteristics of such changes. However, there is a consensus that such changes will be large, significantly amplified towards polar regions in fall, winter and spring seasons and accompanied by a major adjustment in global rainfall patterns. The range of estimates for the average global surface temperature rise for a CO_2 doubling varies from 1 degree C to 5 degrees C and higher (Jaeger, 1988). Most model results also suggest a migration of mid-latitude North American storm tracking northward, resulting in a drier mid-continent and a wetter sub-Arctic (Schlesinger et al, 1988).

Among the most important considerations in assessing the implications of climate change is the rate of such change and the manner in which it affects the pattern of extreme climatic event occurrences. Recent analysis of the possible rates of global climate warming during the next few decades suggest a 95% probability of values between 0.06°C/decade (low emissions, low climate response scenarios) to 0.8°C/decade (high emissions, high climatic response scenarios). The middle scenario, indicating a rise of 0.3°C/decade, would cause an incremental warming over current global mean temperatures of 0.4°C by 2000 AD, 1.2°C by 2025 AD and close to 2.0°C by 2050 AD (Jaeger, 1988). Studies into the effect of typical scenarios for a doubled CO_2 environment on the population distributions of extreme events at specific locations in Canada illustrate how such changes may affect day-to-day regional climates. As expected, frequency and duration of heat spells in summer rise substantially, while the very cold periods of winter become less frequent and more milder. Investigations into the effect of warmer climates on western drought also suggest that, if rainfall amounts do not change significantly, frequency and severity of droughts would increase substantially (Williams et al, 1988).

Climate trends of the past decade indicate that a global climate warming is already in progress. Global temperatures have warmed by 0.4 to 0.5 degrees C over the last century (Figure 1). The six warmest years over that time period have occurred in the 1980's. Although this trend is consistent with model prediction of expected response of climate to changes in greenhouse gas concentrations to date, they are also still within the realms of long-term climate variability, and could be explained by combinations of natural causes for change. While some scientists are already preparing to give the credit to the enhanced greenhouse effect, most feel such conclusions are premature (Hansen et al, 1988; Hanson et al, 1989; Wigley et al, 1985).

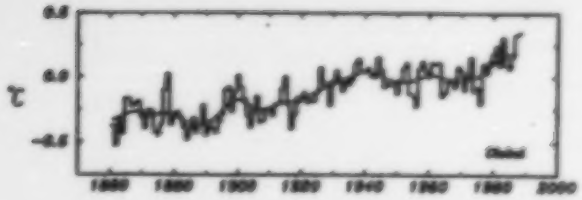

Figure 1. Global mean surface temperature trends since 1860 as compiled by Jones et al (Kerr, 1989).

Numerous studies have attempted to evaluate how the above changes, should they happen, might affect natural global ecosystems and humans (Bolin et al, 1986; Environment Canada, 1986; Jaeger, 1988; Perry et al, 1988; EPA, 1988). Many of the consequences are potentially positive. Direct effects of higher CO_2 levels on plants, for example, are beneficial for improved growth and drought tolerance. Warmer temperatures will improve growing seasons in cooler climates, while making polar regions more accessible to marine transportation. However there is great cause for concern in other domains. With almost 50% of the world's human population located along the ocean coastlines, the possibility of a 1 metre or more rise in sea levels has very ominous implications, particularly for low-lying countries such as Bangladesh, Egypt, the Maldives and the Netherlands. Redistribution of rainfall will decrease drought stress in some areas and turn others into deserts, dramatically changing the global pattern of food production and distribution. Slow forest response to climate shifts may result in large-scale dieback along the warm margins of current ecosystems. Heat stress, increased disease, poorer water quality and more frequent severe tropical storms could have major implications for human health and life. Of greatest concern is that the changes in many cases may be too rapid to make adaptation possible, hence a high risk for catastrophic consequences.

RESPONSE: IMPLICATIONS FOR ENERGY

The above scenarios, together with the evidence that risk of large climate change is significant, led participants at the World Conference on the Changing Atmosphere, held in Toronto in June 1988, to conclude that the "ultimate consequences could be second only to nuclear war," thus representing a major threat to global security. They further stated that "it is imperative to act now" (WMO, 1989). A number of Conference recommendations on the specific actions to be pursued are of particular significance to energy. These include:

- development of an umbrella framework Convention for the protection of the atmosphere.
- reduction of CO_2 emissions by 20% of 1988 levels by 2005 - half of these reductions to be achieved by improved efficiency, the rest by altering energy supply sources.
- significantly increased research funding for renewable energy.
- reduced deforestation and increased afforestation.
- establishment of a World Atmosphere Fund, partly through taxation of fossil fuels, to provide resources required for action.

During the past six months, several other legal/political gatherings have addressed the concerns about global climate change and have repeated a number of the above recommendations (Legal and Policy Experts, Ottawa, February, 1989; UN General Assembly, January, 1989; The Hague Declaration, March, 1989). These collectively reflect a new interest and political will within the international community to respond to growing concerns about environmental issues, particularly those related to the atmosphere - a community that includes organizations such as the United Nations and its member agencies as well as OECD, IEA and IAEA.

When considering the implications that concern about climate change and the emerging desire for responsive action has for Canadian energy policies, there are a number of important factors that must be kept in mind.

i) Canada as a nation is a low emitter of CO_2, releasing about 2% of global emissions (Doucet, 1988). Hence any attempt on the part of Canada to help reduce global emissions only makes sense if pursued as part of an international strategy.

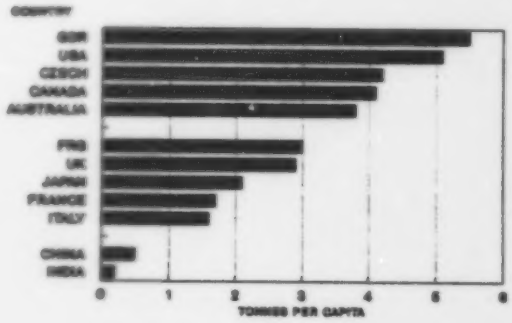

Figure 2. Comparison of the national annual per-capita emissions of CO_2 of the five highest emitting countries, several other OECD nations and two important developing nations.

ii) Canadians, on a per-capita basis, are among the highest emitters of CO_2 in the world (Figure 2). The average Canadian emits about twice as much CO_2 per year as his/her West European or Japanese counterpart, despite similar standards of living (Marland, 1989). Hence Canadian action to reduce emissions may be a pre-requisite to achieving credibility in related discussions in the international community.

iii) Improved efficiency in energy use not only

reduces CO_2 emissions, but reduces release of other pollutants, conserves resources and in general makes economic sense.

iv) Some fossil fuels emit more CO_2 per unit of energy produced than others (Doucet, 1988). Natural gas is the most efficient, with coal and synthetic fuels being the least efficient (Figure 3).

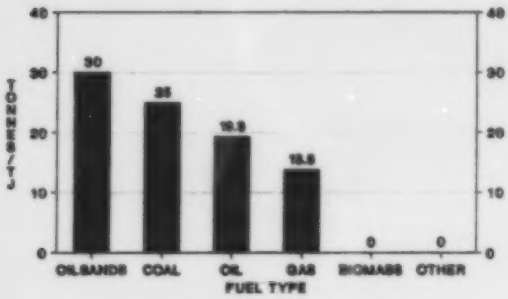

Figure 3. Relative CO_2 emissions per unit of energy (terrajoule) for various energy types. Note that oil sands emission can be up to 30% higher than for coal, coal emissions vary from 28.0 (lignite) to 23.9 (bituminous) tonnes/TJ and biomass produces zero net emission only if regenerated.

v) All biomass energies are carbon-based and hence release carbon during combustion. However, if the biomass is regenerated as a renewable resource, the CO_2 is effectively recycled, with no net long term addition of CO_2 to the atmosphere (Walsh, personal communications).

vi) Non-carbon based renewable energies (wind, solar, hydro-electric, etc) and nuclear energy do not emit CO_2.

vii) Other environmental effects of alternatives to fossil fuels must be carefully considered.

Selection of the best energy options for Canada to follow, should it endeavor to meet the 20% reduction challenge, will need extensive study and discussion. This process has already been started with the establishment of the national Task Force on Energy & Environment, mandated to assess the implications of such a 20% reduction for Canadian energy policy. The above factors clearly indicate that goal may be much easier for Canada to meet than for many other countries. They also suggest that energy efficiency and renewable energy may assume a very important role in achieving these targets.

CONCLUSIONS

The scientific understanding of the global climate system and its response to man-made changes in the atmosphere is still very inadequate. However, the evidence that humans are dramatically changing the characteristics of the atmosphere is is real and the probability that continued change will cause major changes in global climate is high. The risks involved are likely to be considered unacceptable, necessitating global action to protect the atmosphere. Such action has major implications for energy policies in Canada. The likely result will be a much more energy efficient Canadian society and a transition from high CO_2 emitting energy sources such as coal and synthetic fuels to natural gas, renewables and other environmentally safer energy sources.

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PETROLEUM PRODUCTS AND THE CANADIAN ENVIRONMENT

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(PACE)

INTRODUCTION

Petroleum products play a vital role in Canadian society. Our economic and industrial strength, our agricultural riches, our vast transportation systems all rely on the ready availability of petroleum fuels, lubricants and a host of other petroleum products. Indeed, our society tends to take these products somewhat for granted - they are always there when you need them.

Virtually every Canadian enjoys the benefits of a reliable supply of petroleum products. Yet, these benefits are not available without some risks. One subject of great concern to Canadians is our environment. A safe, clean environment is part of the Canadian identity. Threats to our environment are not taken lightly.

The petroleum products industry in Canada - the refining and marketing, or "downstream" operations of the industry - has long been concerned about the potential impacts of its operations on the environment and on human health. These potential impacts are the costs that sometimes accompany the benefits of petroleum products. These concerns led to the creation of PACE in 1971 as a rather unique organization - a voluntary, not-for-profit association of major petroleum products companies dedicated to promoting the principles and science of environmental conservation, and occupational health.

Over the last eighteen years, PACE has proved that "working for a better environment" is more than just a slogan. It is our reason for existing. Many hundreds of volunteer experts from member companies have contributed countless thousands of hours working on a wide variety of projects aimed at improving our technical knowledge and improving the environmental performance of the industry. Their legacy is a body of over 100 technical reports and training programs which have helped the petroleum products industry become one of the most environmentally responsible sectors of Canadian industry. PACE now distributes annually over 10,000 copies of its reports, manuals and training programs to member companies, governments, other industries, consultants and the public.

Lets look briefly at just two areas that have benefitted from our environmental protection programs - surface water quality and waste management.

Surface Water Quality

The petroleum refining industry, in the mid - 1970's embarked on a major program to install state-of-the-art secondary treatment processes at every refinery which directly discharged liquid effluents to surface water bodies. With these systems in place, it is virtually unheard of for any refinery to fail the 96 hour rainbow trout toxicity test for undiluted effluent. Detailed sampling and analytical work for a long list of potential trace contaminants in effluents was initiated by PACE in 1981, years before the MISA program was conceived by the Ontario government. The carcinogenic potential of treated refinery effluent was studied for us by McMaster University, and found to be lower than the drinking water in major Canadian cities,

including Ottawa. The performance of the refining industry was publicly commended by the federal Environment Minister when the most recent environmental compliance report was released. The investments and efforts have paid off and the environment is the beneficiary.

Waste Management

PACE has developed two comprehensive sets of waste management guidelines that, together, cover every operation of the downstream petroleum industry. Key to these guidelines manuals are some 88 waste data sheets that convey information such as:

- name and synonym,
- physical and chemical data,
- hazardous and personal protection,
- handling and storage,
- transportation,
- treatment and disposal recommendations,
- selected references for each waste.

These guidelines have been enthusiastically received by Canadian, U.S. and European companies. We know of no other industry which has so thoroughly documented its wastes. We are already in the process of updating the guidelines to include information related to WHMIS - the Workplace Hazardous Materials Information System and will continue to update them as new information becomes available.

These are but two of many environmental areas in which the industry has been busy. Every step of the entire life cycle of petroleum products has been studied, from manufacturing to end disposal, and new work is continually initiated. Even during the recent periods of tremendous price instability in the petroleum industry, the level of funding devoted to environmental protection activities continued to grow significantly. In PACE, for example, our annual budget has more than doubled in just three years. The commitment is real.

Through the cooperative programs of PACE, individual company initiatives, major investments, and work with governments on the development of sound environmental regulatory programs, our industry has shown that environmental protection is a serious part of our business - a business that we would like to see stay in business for a long time.

Sustainable Development

The new buzz word of environmentalists, politicians and just about everyone else is sustainable development. It is a serious concept that is widely recognized but little understood. Depending on the sector of society that you represent, you may have a very different interpretation of what sustainable means than someone else will. For us in the non-renewable resource sector, the focus must be on environmental sustainability - the anticipation and prevention of environmental degradation coupled with conservation and the efficient use of resources. Lets look at these topics for a few minutes.

Anticipation and Prevention

We have already talked about past performance. What are the issues of today and tomorrow? For us, the biggest set of issues focus directly on the mainstream of our production - petroleum fuels. In the aftermath of the public debate over the phase down, and now the phase out of leaded gasoline, we realized that a number of issues were starting to evolve with regards to gasoline and diesel fuel. Concerns about urban air pollution, ground level ozone and acid rain were being expressed at the same time as concerns about other components or physical parameters of petroleum fuels such as benzene, volatility and sulphur content. PACE became very concerned that the typical regulatory approach to these issues - one at a time - simply wasn't going to work. Experience with lead phaseout shows clearly that a change to any one fuel specification should not be looked at in isolation from its effect on other specifications. Many of these components and parameters are inextricably linked. We believed that a new approach was needed, one that would integrate the results of research and study of a variety of concerns, and devise solutions which

would provide a better overall degree of environmental benefit at an economically achievable cost to the industry and consumers.

Last summer, PACE proposed to Environment Canada that we establish a jointly managed, jointly funded integrated study of transportation fuels to achieve the foregoing objective. We are pleased that the response has been very positive, with strong support from Energy Mines and Resources Canada and Health and Welfare Canada as well. A work plan is now being developed, funds are being committed, and specific working groups are being formed. Fuel components on the recently released Priority Substances List will be an early priority of the study.

We believe that the concept of this study is unique for environmentally driven issues in Canada. It is a good example of the new ways of thinking that are needed to take effective and efficient action to protect our environment.

Conservation and Efficiency

Energy conservation is nothing new. Moves to improve energy efficiency of cars, homes and industries have been very successful. Off oil policies have been equally effective and have forced significant rationalization in our industry. We are today a leaner, more efficient supplier of energy and that is good. Increased energy efficiency is a goal worth pursuing for Canada, particularly when one looks at the looming potential for global warming - the greenhouse effect. We know that fossil fuels are a source of several of the green house gases. When combined with other current global concerns like deforestation, a picture begins to emerge that is not pleasant to contemplate. The scientific debate on global warming is an active one which other speakers are addressing here today.

PACE is closely monitoring developments in Canada and, through membership in the International Petroleum Industry Environmental Conservation Association, or IPIECA, is contributing to the development of international understanding of global warming. For our industry, we believe the cornerstone of policy should be continued emphasis on energy conservation and efficiency. Much has been accomplished, more can be done. After all, the raw materials for our products are of finite supply. It is in our own longer term interest to make those supplies last. As we said earlier, we want to stay in this business.

Conclusions

In conclusion, we in the petroleum products industry have invested heavily in the development and application of new scientific knowledge and have made significant progress in minimizing the environmental impacts arising from the manufacturing and use of our products. We understand and appreciate the importance of our environment and welcome the new political profile it has finally earned.

I'm sure everyone accepts that various energy sources will come and go in the ongoing energy equation. Bioenergy may earn a significant piece of the action. All that we in the conventional energy industries ask for is a fair and level playing field. Lets make sure that other emerging energy sources are subjected to the same full life cycle environmental scrutiny as the fossil fuels have been and are continuing to receive. The old cliche "from the frying pan, into the fire" isn't one that we want our descendants to use in referring to the environmental consequences of our energy choices today.

ENERGY POLICY AND THE SECOND LAW: TIME TO ANTE UP

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The prevailing scientific or Cartesian world-view promotes economic and energy policies which inevitably contribute to ecological destruction. These policies implicitly assume the economy operates as a mechanical system characterized by complete reversibility. In reality, the economy is a thermodynamic system sustained by irreversible one-way flows of high-grade energy and material. Industrial economies therefore consume "the environment" from within and at present rates of consumption, threaten permanently to impair the capacity of the biosphere to maintain itself. Radical changes in economic and related energy policies will therefore be necessary to restore the integrity of the biosphere and place society on a sustainable development path. Examples are discussed.

PURPOSE AND SCOPE

This paper interprets the relationship between ecological decline and economic and related energy policy in Canada in light of the Second Law of Thermodynamics. The intent is to make a practical contribution to the current debate on "sustainable development" inspired by the recent publication of Our Common Future (WCED 1987), the Report of the World Commission on Environment and Development (the Brundtland Report).

My basic premise is that our present "world-view" is woefully inadequate to resolve the economy-environment conundrum. Society operates from an outdated mechanistic perception of the economy and has only a rudimentary understanding of the dynamics of the economy-environment relationship. If this premise is correct, our present understanding of the so-called "environmental crisis" is dangerously superficial and the possibility of sustainable development based on the growth assumptions of existing neo-classical economic models may be illusory.

To document this argument, I trace present economic thinking to its roots in 17th Century mechanical empiricism and examine the present-day economy-environment relationship in light of the Second Law of Thermodynamics. This comparison reveals the seeds of our environmental crisis and suggests policy alternatives that better reflect thermodynamic reality.

ON WORLD-VIEWS: THE CULTURAL BASIS OF REALITY

The way in which societies relate to the rest of reality is profoundly affected by an elaborate set of unconscious "facts" and unquestioned assumptions. These are derived ultimately from the shared experience of a people in the course of their social evolution and are transmitted culturally to each new individual as s/he matures in that particular milieu. Such deep-rooted beliefs, attitudes, and perceptions determine how people react, more or less automatically, to both the new and the familiar in the conduct of their day-to-day affairs. It is its "world-view," (or cosmology) that shapes a particular culture's social relationships, its political institutions, and the nature of its economic enterprise.

It is important to realize that there may be as many world-views as there are cultures or societies, each based on a different history and experience of the wider environment. We must also recognize that any world-view only more or less coincides with physical reality. Our most sacred beliefs, however well sustained by the evidence to date, may simply be wrong.

Often it is of no great consequence to

society when even its profoundest beliefs (e.g., "the world is flat") depart from reality. On the other hand, certain activities consistent with the prevailing world-view may eventually lead to significant problems. In these circumstances, society must modify its world-view to conform with the new reality. As we shall see, such is the case with our environment-economy conundrum.

SCIENTIFIC MATERIALISM AND THE MECHANICAL CLOCKWORK UNIVERSE

The scientific or Cartesian world-view that presently dominates western society is characterized by a mechanical view of the universe as "a vast machine, wound up by God to tick forever, and consisting of two basic entities: matter and motion" (Berman, 1984, p. 21). This vision dates only from the 17th Century and is most closely associated with Rene Descartes, Francis Bacon and Isaac Newton.

Descartes set the stage with his division of reality into the independent realms of mind and matter and his quest for a universal mathematics to measure and order the external world. The ultimate rationalist, Descartes saw man's activity as a thinking being as purely mechanical. The mind has a certain (reductionist) method and confronts the world as a separate object. "It applies this method to the object, again and again and again, and eventually it will know all there is to know" (Berman, p. 20).

Descartes' contemporary, Francis Bacon, represents the empiricist pole. Reasoning that to know nature one had to "vex" it, Bacon gave us the essence of experimental method. He also gave the new science its raison d'etre. According to Bacon, knowledge should be put to work allowing humankind to take command over the natural world and its mechanical powers. "From this perspective, knowledge is regarded not as an end but as a means, expressed and applied in technology, by which humans assume power over the material world" (Jones 1988, p. 236).

But it was Newton who ultimately succeeded in validating the Cartesian view of the Universe. With his Principia (1696), Newton revealed the seemingly universal laws of mass and motion that describe the universe as a vast mechanical machine behaving according to strict mathematical rules. In effect, "by separating and then eliminating all the qualities of life from the quantities of which they are a part, the architects of the machine paradigm [left us] with a cold, inert universe made up entirely of dead matter" (Rifkin, p. 22). The industrial age is testimony to the success of this materialist paradigm.

The Modern Legacy: Economics as Mechanical Analogue

Modern economics owes much to the mechanical world-view. The founders of the neo-classical school, impressed with the spectacular successes of Newtonian physics, strove to create economics as a sister science, "the mechanics of utility and self-interest" (Jevons 1879, cited in Georgescu-Roegen 1975). The major consequence of this mechanical analogue is an entrenched view of economic process as "a self-sustaining circular flow between production and consumption within a completely closed system." By this perception, supply and demand functions continually readjust to each other, "everything. . .turns out to be just a pendulum movement. One business 'cycle' follows another. . . If events alter the supply and demand propensities, the economic world returns to its previous position as soon as these events fade out." In short, "complete reversibility is the general rule, just as in mechanics" (Georgescu-Roegen 1975, p. 348, emphasis added). This perspective sees human impacts on environmental process as ultimately inconsequential. If we press the environment too far, a simply retraction (e.g., clean-up) will bring us safely back again.

A major corollary of equilibrium mechanics is that continuous material growth becomes theoretically possible (see Simon and Kahn 1984). Many economists seem to believe "not only in the possibility of continuous material growth, but in its axiomatic necessity" (Georgescu-Roegen 1977). This "growthmania" (Mishan 1967) "has given rise to an immense literature in which exponential growth is taken as the normal state of affairs" (Georgescu-Roegen 1977).

A CONTRASTING REALITY: THE THERMODYNAMICS OF SUSTAINABLE DEVELOPMENT

The emerging ecological crisis suggests fatal flaws in the Cartesian world-view that require it be adapted to the new reality. Most important is the fact that economic theory essentially ignores the Second Law of Thermodynamics: In any closed isolated system, available energy and matter are continuously and irrevocably degraded to the unavailable state. (See Georgescu-Roegen 1975, 1977.) The reality is that the Second Law (the entropy law) is the ultimate regulator of economic activity.

Since all modern economies are dependent on stocks of non-renewable material and energy resources, the Second Law declares that they continuously degrade and consume the very resource base which sustains them. So much for reversible equilibria. The first effect of the Second Law is to declare that economic "production" is really "consumption!"

All economic activity contributes to a constant increase in global net entropy (disorder), through the continuous dissipation of free energy and matter drawn from the biosphere. Thus, contrary to the assumptions of neo-classical theory:

- there is no equilibrium of any sort in the material relationship between industrial economies and the environment; and
- sustainable development based on prevailing patterns of resource use is not even theoretically conceivable.

Autopoiesis: The Special Case of Ecosystems

In contrast to economic systems, ecosystems seem to be inherently self-sustaining and self-organizing, and therefore to contribute to a reduction in global net entropy. This property of "autopoiesis," by which the biosphere produces itself, is dependent on the maintenance of key organizational relationships and a minimal

level of structural diversity.

Autopoiesis is possible only because ecosystems, unlike economic systems, are driven by an extra-terrestrial source of free energy, the sun. Through photosynthesis, a steady stream of solar energy sustains essentially all biological activity and makes possible the diversity of life on earth. Thus, in contrast to economic systems, ecosystems steadily contribute to the accumulation of concentrated energy, matter, and order within the biosphere. In thermodynamic terms photosynthesis is the most important (if not the only) productive process on the planet.

Photosynthesis is the ultimate source of all renewable resources used by the human economy. Moreover, since the flow of solar radiation is constant, steady, and reliable, resource production in the ecological sector is potentially sustainable over any time scale relevant to humankind.

But only potentially. Ecological productivity is ultimately limited, in part, by the rate of energy input (the "solar flux") itself. Ecosystems therefore do not grow indefinitely. Unlike the economy, which consumes its "environment" and expands through intrinsic positive feedback, ecosystems are held in steady-state or dynamic equilibrium by limiting factors and negative feedback.

This is significant because human beings and their economies are now a dominant component of all the world's major ecosystems. Since these economies are growing and the ecosystems within which they are embedded are not, the consumption of ecological resources everywhere threatens to exceed sustainable rates of biological production. Moreover, over-exploitation is exacerbated by pollution which impairs the remaining productivity of ecosystems.

This last point is critical. The mechanical paradigm essentially ignores the downstream consequences of material dissipation (pollution). By contrast, the thermodynamic perspective regards the capacity of the biosphere to absorb and recycle this "waste" as an essential resource. While traditional economics argues that technology and substitution eliminate any concern about material resource scarcity, it is silent about the growing scarcity of process resources. Present trends suggest we have exceeded the recycling capacity of the biosphere and there is no substitute.

Clearly, any human activity dependent on the consumptive use of ecological resources (forestry, fisheries, agriculture, waste disposal, urban sprawl onto agricultural land) cannot be sustained indefinitely if it consumes not only annual production (the "interest"), but also cuts into the capital. Herein lies the essence of our environmental crisis. Persistent trends in key ecological variables - falling water tables, declining soil fertility, increasing CO_2 levels - indicate that we have not only been living off the interest but also consuming our ecological capital. Exceeding the planet's carrying capacity in this way is the inevitable consequence of exponential material growth in a finite environment.

Intensive Energy Use: Accelerating Ecological Decline

The industrial age was made possible by and remains dependent on the intensive use of hydrocarbon energy. Without access to available energy in the form of immense stocks of coal, oil, and natural gas (fossil solar energy) we would not have witnessed the explosive accumulation of capital, the steady rise in material standards of living, and the exponential growth of the human population that have characterized the last two centuries.

Unfortunately, as we have previously noted, the second law dictates that this enormous expansion of human capital could only be purchased at a much greater cost of permanently degraded resource capital. We are becoming acutely aware of the direct effects. A 25% increase in atmospheric carbon dioxide threatens to destabilize global climate; sulphur and nitrogen oxides are leading components of acid rain and hence to forest dieback and the death of lakes in much of the industrial world.

But how many people think of the indirect contribution of intensive energy use to most of the other ecological problems confronting the world. Soil deterioration everywhere has been greatly accelerated by the energized mechanization of agriculture and forestry (50% of the natural organic and nutrient content of Canada's prairie soils have been dissipated through cropping, erosion, and cultivation-induced oxidation); the depletion of numerous commercial fisheries and overharvesting of forest resources is only possible because of energy intensive harvesting technologies; the extinction of species results mainly from massive habitat destruction to make room for further energy-subsidized human activity; many toxics accumulating in food chains are the previously dispersed by-products of fossil fuel-based industrial activity. It is difficult to think of a significant environmental problem that cannot in some way be traced to the intensive use of energy by industrialized society.

The implications of this facet of the second law are sobering indeed. In thermodynamic terms, intensive energy use has served mainly to accelerate the rate at which the human enterprise dismantles the biosphere and inhibits its remaining productive capacity. Carried far enough, this can only destroy the autopoietic organization of the global ecosystems upon which humanity is dependent.

There is a second lesson here for those who warm to the possibility of our discovering some new boundless energy source to replace rapidly depleting stocks of oil and gas. (Current excitement over the possibility of "cold fusion" is a case in point.) If any such energy bounty serves only further to underwrite the material growth paradigm (i.e., to preserve the status quo), the destruction of the biosphere may well be assured! Technological magic bullets have an irritating tendency to ricochet unpredictably.

The Bottom Line

We live in a world in which the 26% of the world's population living in developed countries consumes 80-86% of non-renewable resources and up to 34-53% of food products (WCED p. 33). Accordingly, the Brundtland Commission proposed a five- to ten-fold expansion of industrial activity to bring the developing world up to first world standards of living. The present analysis suggests this may be physically impossible - we have already exceeded important thermodynamic limits to growth. Reducing the present gap in standards of living between the rich and poor (between and within nations) may therefore require that the rich reduce future expectations, and even present consumption, so that the poor may enjoy a fairer share of the world's resources.

CONCLUSIONS: THE POLICY IMPLICATIONS OF THE ENTROPY LAW

Industrial society has historically ignored the second law at great unrecognized cost. We've long enjoyed a free ride for which we now have to ante up. Forest products, food, and manufactured goods are undervalued in the marketplace to the extent the prices we pay do not include the entropy costs of resource maintenance. The family's second car may represent capital that was not plowed back into silviculture, soils management, and waste control.

It is a tribute to the staying power of the mechanical paradigm that even energy policy remains uninformed by the second law. The cold fact is that our energy-subsidized economy is founded on thermodynamic flows, not the assumed mechanical equilibria. This thermodynamic interpretation of economic process even suggests a new definition of sustainable development as development that minimizes resource use and the increase in global entropy. The following energy-related policy suggestions illustrate the new direction society must follow if we are even to approach such thermodynamically sustainable development:

- A massive effort should be put into energy conservation in Canada. Canadians consume 2.5 times as much energy per capita as western Europeans (World Resource Institute 1986, p. 103). Serious conservation efforts could eliminate domestic demand for new energy developments for many years.
- All subsidies of fossil fuel development should be withdrawn and the funds redirected into research and development of renewable energy and energy efficient technologies and products. This effort would create more and better jobs than today's hydrocarbon mega-projects, while developing Canadian expertise and products for which there will likely be great demand in the 21st Century. (Operating from the illusions of the Cartesian mind-set, Canada continues to subsidize hydrocarbon mega-projects and has systematically dismantled its alternative energy research capacity in recent years.)
- Environmental assessments of energy projects should be extended to include the downstream impacts (entropy costs) of actually using the resources produced.
- Serious consideration should be given to re-establishing domestic natural gas reserve requirements before declaring any natural gas surplus for export. Natural gas is the most ecologically benign hydrocarbon fuel (low CO_2 output per unit energy) and hence the most desirable for intensive uses during the transition to renewable energy. This and related entropy considerations should be primary in any decision by the Natural Energy Board to allow the export of Beaufort Sea hydrocarbons into the US market. (It would be a supreme irony if the chief beneficiaries of the 1970's $billions in Canadian tax subsidies for frontier exploration in the name of national self-sufficiency turned out to be US consumers.)
- An entropy tax should be imposed on all hydrocarbon fuels; the rate for each fuel type should be proportional to the carbon/hydrogen ratio (CO_2 output per unit energy), and gross revenues adequate for the purpose outlined below.
- The revenues raised through the entropy tax should be formally dedicated to reforestation in Canada (and elsewhere as appropriate). Sufficient forest should be replanted to extract from the atmosphere a quantity of CO_2 equivalent to that discharged into the atmosphere by the consumption of the fossil fuel. (There is a precedent. Applied Energy Services of Arlington, VA. will plant a carbon sink forest in Guatemala to compensate for the CO_2 that will be discharged over the 40-year life of its new coal-fired power station in Connecticut [Branford 1988]).
- Similar tax and market incentives should be devised to compensate for the entropy costs of other economic activities. For example, food prices generally reflect only the direct labour and material costs of production, not the hidden costs of soil degradation, ground water pollution, etc. Can food markets be restructured to capture the revenues necessary for a national agricultural soils rehabilitation program?

Such policy initiatives are consistent with the need under sustainable development to minimize resource throughput and internalize the entropy costs of economic activity. Heretofore economic theory has essentially ignored the environmental costs of energy use and simply not recognized the value of nature's services in producing and maintaining the conditions necessary for life.

True environment-economy integration means that the economy must be restructured to preserve rather than consume the biosphere. The use of a hydrocarbon entropy tax to reforest the nation acknowledges that even present levels of fossil energy use have overwhelmed the carbon cycle and that consumers should pay to restore the service. It also recognizes that in future the most economically significant role of forest management may be the stabilization of the atmosphere and global climate patterns. Indeed, the value of growing forest as a carbon sink may well soon exceed its economic value for fibre production. (Trees are about 50% carbon dry weight, or 1/4 tonne per cubic metre.)

Paying the true cost of fossil fuel use has the additional advantage of reducing demand and

therefore the rate of atmospheric CO_2 loading, and of improving the competitive position of ecologically benign renewable alternatives in the marketplace.

The diversion of real wealth into biosphere restoration in the industrial countries will clearly require significant restructuring of the economy. However painful this might be (though there are also economic opportunities) the entropy law says we have little choice. Even the Brundtland Commission recognized that for sustainable development the quality of development, particularly in the first world "would have to change radically" (WCED 1987, p. 213). Difficult political decisions in the developed North are also necessary to send a strong signal to the third world that we are serious about sustainable development on our own turf. What could be more hypocritical than Canadians pleading with Brazil in the name of the biosphere to halt the destruction of the Amazon rain forests while continuing the razing of our own?

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A TECHNICAL AND ECONOMIC ANALYSIS OF DIRECT BIOMASS LIQUEFACTION

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ABSTRACT

This paper discussed the results of a technoeconomic assessment of direct biomass liquefaction processes converting wood and peat to gasoline and diesel fuels. The study was carried out by the Working Group of the International Energy Agency, Direct Biomass Liquefaction Activity, in which Canada, Finland, Sweden, and the United States participated. The assessment covered three steps for each process from feed to final product:

1. Primary liquefaction to an intermediate liquid product.
2. Upgrading to a deoxygenated product.
3. Refining to gasoline and diesel fuel.

Cette communication examine les résultats d'une évaluation technoéconomique des procédés permettant d'obtenir directement de l'essence et du carburant diesel par liquéfaction de bois ou de tourbe. L'étude a été réalisée par le groupe de travail de l'Agence internationale de l'énergie, dans le cadre du Project de liquéfaction directe de la biomasse auquel participent le Canada, la Finlande, la Suède et les Etats-Unis. L'évaluation porte sur trois étapes pour chaque procédé permettant de transformer la charge d'alimentation en produit final, soit (1) la liquéfaction primaire qui permet d'obtenir un produit liquide intermédiaire, (2) la valorisation en produit exygéné et (3) le raffinage en essence et en carburant diesel.

A TECHNICAL AND ECONOMIC ANALYSIS OF DIRECT BIOMASS LIQUEFACTION

INTRODUCTION

Liquid fuels from biomass are expected to play a major role in the energy future of industrialized countries[21]. These fuels offer many advantages over raw biomass as an energy product. For example, the liquid hydrocarbon product is compatible with the hydrocarbon fuels currently marketed that are produced from petroleum. Removal of oxygen and adjustment of the hydrogen to carbon ratio during the liquefaction and upgrading steps results in a product mixture of true hydrocarbons that could be substi-tuted directly into the existing fuels market. The energy density of liquid fuels is higher than raw biomass because of both chemical and physical characteristics. The heat of combustion of dry wood, for example, is half that of gasoline, while the bulk density of solid biomass is much less than conventional liquid fuels since plant structures have high porosity. Other advantages of liquid fuels include stability during long storage periods and ease of transportation.

This paper is based on the results of Stage 2 of a cooperative activity carried out by Canada, Finland, Sweden, and the USA[13]. In an earlier study (Stage 1), compiled in 1983[14], process concepts studied in the four countries were reviewed and evaluated. The results of that study indicated that direct liquefaction of biomass could be used to produce liquid boiler fuels with an overall energy efficiency of 50% to 60%. It was also concluded that upgrading the biomass crude oil to gasoline-like products would be possible, although much less experimental work had been done in that field. Since the earlier study, much progress has been made in the field of biomass liquefaction[3,20].

APPROACH FOR TECHNOECONOMIC ASSESSMENT

The production cost for synthetic gasoline or diesel fuel from the biomass feedstock was determined for two alternative process concepts Atmospheric Flash Pyrolysis (AFP) and Liquefaction In Pressurized Solvent (LIPS). For

the processes the conversion to gasoline required three steps: liquefaction, upgrading, and refining. The production cost was determined by estimating the capital and operating costs for the liquefaction, upgrading, and refining plants. Where applicable, credits were included for process byproducts. The capital and operating costs for processing the plant emissions and effluents to conform with environ-mental restrictions in the participating countries were also included. The plant capacities were based on processing 1000 dry ton/day of biomass feed.

Capital Costs

The capital costs for each plant were determined by summing the costs related to the major pieces of equipment. The equipment was sized from material and energy balances completed for each process. The equipment costs were then estimated using published data from a reference base compiled by the Working Group[13]. In a few cases where published data were not available, equipment costs were determined by obtaining quotes from manufacturers. These cases are noted in the reference base. The costs for plant instrumentation and control were determined by summing the instrumentation costs associated with each piece of equipment. These costs are also listed in the reference base.

The total capital investment was determined using the factor method proposed by Guthrie[12]. The base equipment costs were multiplied by a direct cost factor, a building factor, a site improvement factor, and a utilities factor to obtain the total direct cost for a piece of equipment. This cost was then multiplied by an indirect cost factor, covering engineering costs and construction overheads, and the resulting sum for each piece of equipment gave the Fixed Capital Investment (FCI) for the plant.

The direct cost factor used was dependent on the particular piece of equipment; these factors were obtained from Cran[4]. The indirect cost factors varied from 1.0 to 1.3, depending on whether the base equipment cost data were for a turnkey unit, an installed unit, or the base equipment only. The factors used for the required buildings, site improvements, and utilities are listed below:

-Buildings1.15
-Site improvement1.06
-Utilities1.16

The Total Capital Requirement (TCR) for a plant was determined by adding to the FCI the startup costs (10% of FCI), the working capital (5% of FCI), and the interest during a 3-year construction period. The costs of land and contingencies were not included in the cost estimate.

Operating Costs

The majority of the fixed operating costs (maintenance labor, maintenance materials, overhead, and insurance) was based on percentages of the FCI. These percentages and the basis for the variable operating costs (feedstock, electricity, and catalyst costs) are listed in the section entitled Bases For Assessment (see Table 1).

The capital charges were added to the fixed and variable operating costs to determine the production cost of the product for each plant. The capital charges are determined by the annuity method, which produces levelized costs; a 20-year plant life was assumed. For the upgrading and refining plants, the production cost of the intermediate product became the feedstock cost for the next step.

Refining Costs

Refining costs were estimated differently as average costs in refineries built to handle 5 million tons of various oils per annum. The cost estimate was based on data supplied by Frumkin[11] on refining oils produced by liquefaction of coal and oils from shale. The refining operation was sub-divided into separate processes, for instance, catalytic reforming, hydroprocessing, and wastewater treatment. Costs were estimated separately for each of the processes. A power of scale of 0.68 was used to calculate costs for different sizes. The yields in each process were based on petroleum refining, and were changed for the different elemental compositions and molecular weight distributions while assuming similar chemical reactivity.

BASES OF ASSESSMENT

Table 1 shows the assumptions and costs of the various parameters used to determine production costs. The feedstock used in the evaluation was eitherwood chips with 50% moisture or milled peat with 50% moisture. Two sensitivity case analyses are included in this paper. First, the effect of the feedstock price was considered because it varied among the participating countries. Secondly, variations in the capital costs (up to 20% high or low) were analyzed to account for the uncertainty of the capital cost estimates.

PROCESSES EVALUATED

The results from the analysis of the AFP and LIPS processes, using a wood or a peat feedstock, are presented here. In the process concepts, catalytic hydrotreating was used in upgrading the products from both processes. The complexity of the refining step, where the finished products were produced, was dependent on the oxygen content of the product from the upgrading step.
Process designs were determined for the

evaluation by scaleup of the process concepts under development at the laboratory-scale and at pilot-scale. Two process design cases were prepared for each process studied. The first case, referred to as "Present" technology, was based on actual experimental data available and utilized equipment already commercially proven for identical or similar applications. The second case, referred to as "Potential" technology, was based on process results determined as feasible to obtain in the future and/or using equipment applications not currently demonstrated at the commercial scale. The achievement of the assumptions used in the Potential cases is thought to be reasonable through future experimental and developmental work.

Atmospheric Flash Pyrolysis of Wood

In the Present case of the AFP process, wood fibers (1 mm particle size) are rapidly pyrolyzed at 500°C to vapors and char. The condensed vapors form the primary tar product, which contains approximately 39% oxygen on a dry basis. The flowsheet for the primary liquefaction step is shown in Figure 1. It is based on processes being developed at the Georgia Tech Research Institute, USA[15], and the University of Waterloo, Canada[19]. The material balance is based on data from a continuous 3-kg/h process development unit, operated at the University of Waterloo. The experimental results were normalized to give a material balance closure of 100% for this evaluation.

In the Present case, the primary oil is upgraded using a two-stage catalytic hydrotreating process, shown in Figure 2. The first stage operates at 250°C as a stabilizing step for the second stage, which operates at 350°C. A conventional sulfided cobalt/molybdenum on alumina, petroleum hydrotreating catalyst is used. The material balance for upgrading the primary oil is based on experimental results obtained at Pacific Northwest Laboratory (PNL) using oil from the Georgia Tech Research Institute[8].

Refining the upgraded product consists of multiple steps including: distillation of the upgraded product, hydrodeoxygenation of the light fraction, hydrocracking of the heavy fraction, catalytic reforming of the gasoline product, and steam reforming of the hydrocarbon gas product to produce hydrogen. A gasoline and diesel product slate is produced.

The flowsheet for the Potential case primary liquefaction step is shown in Figure 3. In this case, the pyrolysis takes place in a circulating, fluidized-bed reactor, which has the advantage of a much greater throughput compared with the fluidized-bed reactor used in the Present case concept. It is assumed that the same physical properties could be obtained in this reactor as those used in the experimental unit, allowing the same material balance and product properties to be used as in the Present case.

In the upgrading step for the Potential case, catalytic hydrotreating takes place under nonisothermal conditions in three reactors operated in series, at 300°C, 350°C, and 400°C, respectively, see Figure 4. Process improvements are assumed, through catalyst development, including a stoichiometrically-balanced mass balance where sufficient byproduct gas is produced to provide for needed hydrogen production. In addition, a higher reactor space velocity is used. The upgraded product is assumed to be primarily a high-octane gasoline requiring no further processing other than distillate fractionation.

Liquefaction of Wood In Pressurized Solvent

The Present case of the LIPS process is based on tests at the Biomass Liquefaction Experimental Facility, Albany, Oregon, USA, in the PERC mode[22]. A flowsheet of the process is shown in Figure 5. Wood chips are ground to less than 0.5 mm and mixed with recycled wood-derived oil. A sodium carbonate catalyst solution and CO/H_2 syngas are added to the slurry prior to preheating. Liquefaction takes place in an upflow tubular reactor at 350°C, 20.5 MPa, with a 20-minute residence time. Gas is flashed from the reactor effluent stream. A portion of the liquid is recycled. Water is separated from the primary oil product and is treated before discharge. The syngas required for the liquefaction and for preheating the slurry is produced by gasifying a portion of the wood feed in an oxygen-blown gasifier. The material balance for the primary liquefaction is based on data from Run TR-12 at the Biomass Liquefaction Experimental Facility. The primary product oil contains 12.7% oxygen on a dry basis.

The primary oil is upgraded by catalytic hydrotreatment as shown in Figure 6. Processing conditions include 400°C, 2000 psig, and liquid hourly space velocity of 0.3 with a sulfided cobalt/molybdenum on alumina catalyst. The material balance is based on experimental results obtained at PNL using product oil from the Albany plant, Run TR-12[1].

Refining the upgraded product to a finished product slate involves multiple steps including: distillation of the upgraded product, hydrocracking of the heavy fraction, catalytic reforming of the gasoline fraction, and steam reforming of the hydrocarbon product gases to produce hydrogen. A gasoline and diesel product slate is produced.

The Potential case for this process is based on the use of an extruder to feed high concentration wood slurries, as tested at the University of Arizona[23]. The flowsheet for this process is shown in Figure 7. The oil phase of the slurry consists of recycled vacuum distillate bottoms. Superheated steam is added to the reactor to provide the reactor heat

requirement. Sodium carbonate is used in this process and is assumed to be recycled entirely in the distillate bottoms. No reducing gas is added to the reactor. The liquid product stream is separated into a distillate product and recycled bottoms in a vacuum distillation tower.

Although the extruder feeding method and reactor system are based on research work by the University of Arizona, sufficient material balance data were not available for this evaluation. Therefore, the material balance for the reactor was based on batch results from the University of Toronto Steam Pyrolysis System[2]. The primary product oil is assumed to have an oxygen content of 23.5% on a dry basis.

Catalytic hydrotreatment is used to upgrade the primary oil under similar processing conditions as the Present case, depicted in Figure 6, based on results obtained at PNL[7]. Process improvements again are assumed through catalyst development, including a stoichiometrically balanced mass balance. A higher reactor space velocity also is used. In this Potential case, the catalyst lifetime is extended to a more conventional turnover basis because of the separation of the heavy ends from the primary product oil through distillation. As a result of the assumed catalyst improvements and the differences in the primary product oil, the upgraded product is primarily a high-octane gasoline requiring no further processing other than distillate fractionation.

RESULTS OF THE ASSESSMENT

Detailed cost estimates for the direct biomass liquefaction processes were made based on the procedures described above. Estimates for both capital and operating costs were prepared. With process designs balanced for both mass and energy, total product costs could be calculated using the predetermined assessment bases.

Capital Costs

A summary of the capital costs for the eight process cases is given in Tables 2 and 3. From these numbers, several important conclusions can be drawn. Considering first Table 2 and the wood processes, the largest difference is found in the potential for process improvement as demonstrated by the difference between the two Present cases and the two Potential cases. This difference results from improvements in the primary liquefaction step and, through improvement in the upgrading step, near elimination of the product finishing requirements. The difference in capital cost between AFP and LIPS is not large when considering the complete process, from wood to gasoline. The capital cost of the primary liquefaction step is much higher for the high-pressure (LIPS) process. However, due to the higher crude product quality (less oxygen) and lower volume flow, the upgrading step requires less equipment and has a lower capital cost compared with the AFP process. Product finishing is nearly the same for both processes.

Product Costs

Annual operating costs for the six cases are summarized in Table 3. The basis for the calculation (feedstock price, interest rate, and electricity price) is given in the table and is defined as the base case. Feedstock cost is the single largest cost item. The cost of capital is the next largest operating cost but is less than 1/4 of the total in the Present cases and decreases to about 1/6 of total operating cost in the Potential cases.

Product costs are presented in Table 4. These costs clearly show the advantage of the AFP process for producing a low-cost primary oil product, and this conclusion carries through to comparisons of product cost on an energy basis and on a product-value basis. The costs of the finished products are much closer in value, but the AFP process still has a lower cost. Since there is no significant difference in the composition of the finished products, comparisons of finished product cost on the basis of tonnage, energy, or value result in the same conclusion. For both processes, the Potential technology case demonstrates a significant advantage in lower product cost.

Process Energy Efficiencies

Calculated energy efficiencies for the four process cases are given in Table 5. Efficiencies of nearly 70% are achievable in the primary liquefaction. Finished product efficiencies of 50% to 60% are expected. The AFP process appears to be more efficient in all cases. The data also show no significant energy value in the byproducts from the wood liquefaction processes, as the efficiencies are the same whether considering liquid products alone or all products. The peat processes, however, produce a larger amount of byproduct char.

Product Cost Sensitivities

Sensitivities of the product costs have been examined in certain cases. The effect of feedstock price is a major consideration for these processes. As noted above, the feedstock is the single largest operating cost and has the largest impact on product cost. In Table 6, Final Product Costs are shown for a range of feedstock prices. The base case price of 30 US$/tonne of wood chips (50% moisture) is indicated. The base case feedstock price is typical for Scandinavia and is about double the market rate in North America. As seen in Table 6, the Final Product Cost is strongly dependent on feedstock price. All four process cases react to changes in the feedstock price in a similar manner.

The effect of capital cost (FCI) on the Final Product Cost is plotted in Table 7 The range of ±20% was selected considering the accuracy of the equipment cost estimates used in this study. Within this range of capital cost variation, the Final Product Costs vary by less than 8% for the Present process cases and 5% for the Potential process cases. Therefore, the Present process cases are somewhat more sensitive to changes in the capital cost than the Potential process cases.

CONCLUSIONS

With direct liquefaction of biomass, synthetic gasoline or diesel oil can be produced with high efficiency (up to 50 to 60%). This efficiency applies to both the AFP process and the LIPS process.

The most promising Present process case for the production of primary liquid (boiler fuel oil) is the AFP process. Using the average spot market price for fuel oil in the period 1977-1987 as a reference, the ratio of product cost to product value is about 1.4 at a wood chip price of 30 US$/tonne (50% moisture), and decreases to below 0.9 for a lower cost of 10 US$/tonne. That is, in this latter case, the process yields a product that is competitive with an equivalent amount (on an energy basis) of petroleum-derived fuel with similar combustion properties.

For production of gasoline by direct liquefaction, the AFP process also appears to be the most economical. With present technology, the estimated ratio between the product cost and the product value (defined as average spot market price for 1977-1987) is about 2.0 for a feedstock price of 30 US$/tonne (50% moisture).

On the basis of sensitivity studies, all the biomass liquefaction processes appear to be more sensitive to feedstock price than capital cost. Although thermochemical conversion processes are generally viewed to be capital-intensive, the range of study of capital cost variability had little effect on the final product cost. However, the cost of feedstock was found to be the largest operating cost, and the final product cost was found to be highly sensitive to feedstock price.

There appears to be a development potential for both the AFP and LIPS processes, allowing a possible cost reduction of 20% to 30% for the products. Of the Potential liquefaction technologies, the AFP appears as the most proven. For the Potential process based on LIPS, the main uncertainty applies to scaleup from laboratory tests, in particular the possibility to achieve the performance measured in laboratory experiments in full-sized reactors. The main uncertainty about use of the Potential AFP process for gasoline production applies to upgrading the primary product.

As far as the most promising strategy for future research and development is concerned, the Working Group concludes that the most promising process for gasoline production by direct liquefaction of biomass is atmospheric flash pyrolysis. The high-pressure processes may have the same future potential, but the research needs and the uncertainties are much greater. It can therefore be recommended that further cooperative research and development should be focused on the AFP process.

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TABLE 1
PARAMETERS USED IN COST BASIS

Plant Capacity	1000 dry tonnes/day biomass feed
Time	September 1987
Place	US Gulf Coast
Currency	United States Dollars
Annual Operating Time	8000 Hours
Labor Rate	20 US$/h including payroll burden
Maintenance Labor	1% of FCI
Maintenance Materials	3% of FCI
Overhead	2% of FCI
Insurance	2% of FCI
Other Fixed Operating Costs	1% of FCI
Catalyst Price	Specified for process operation
Feedstock Price	
Wood chips, 50% moisture	30 US$/tonne
Milled peat, 50% moisture	20 US$/tonne
Electricity Price	0.065 US$/kWh
Interest Rate	10%
Plant Life	20 years

TABLE 2
SUMMARY OF CAPITAL COSTS FOR WOOD LIQUEFACTION PROCESS CASES

	AFP PRESENT	AFP POTENTIAL	LIPS PRESENT	LIPS POTENTIAL
	Millions, US$			
Fixed Capital Investment (FCI)				
Primary Liquefaction	38.9	20.6	65.8	37.8
Crude Upgrading	36.4	26.8	20.9	20.1
Product Finishing	11.4	0.5	11.9	0.6
Total	86.7	47.9	98.6	58.7
Total Capital Requirement (TCR)				
Primary Liquefaction	49.8	26.4	84.2	48.4
Crude Upgrading	46.6	34.3	26.8	26.0
Product Finishing	14.5	0.7	15.3	0.7
Total	111.0	61.3	126.2	75.1

TABLE 3
PRODUCTION COST SUMMARY FOR WOOD LIQUEFACTION PROCESS CASES

	AFP PRESENT	AFP POTENTIAL	LIPS PRESENT	LIPS POTENTIAL
	Millions US$ per year			
Fixed Operating Costs				
Operating Labor	6.68	6.43	5.58	4.73
Maintenance Labor	0.06	0.49	0.99	0.59
Overheads	1.74	0.96	1.98	1.18
Maintenance Materials	2.60	1.44	2.96	1.76
Taxes & Insurance	1.74	0.96	1.98	1.18
Others	0.06	0.49	0.99	0.59
Total	14.48	10.77	14.48	10.83
Variable Operating Costs				
Feedstock	20.00	20.00	20.00	23.30
Electricity	4.89	3.57	9.72	10.14
Catalyst	0.30	0.02	2.36	0.01
Sludge Disposal	0.16	0.02	0.04	0.09
Fuel Cost	0.39	0.06	1.32	0.06
Total	25.74	23.67	33.44	33.60
Capital Charges	12.96	7.17	14.75	8.78
Total Production Cost, Finished Product	53.18	41.61	62.67	52.39

Wood Price, US$/tonne, (50% moisture)	30
Interest Rate, %	10
Electricity, US$/kwh	0.065

TABLE 4
COMPARISON OF BIOMASS LIQUEFACTION COSTS
BASE CASE ASSUMPTIONS

- - W O O D - -

	AFP PRESENT	AFP POTENTIAL	LIPS PRESENT	LIPS POTENTIAL
Product Costs, US$/tonne				
Primary Product	150.0	131.9	423.3	298.1
Final Product	673.8	514.5	815.0	584.7
Product Costs, Cd$/liter				
Primary Product	0.20	0.18	0.58	0.41
Final Product	0.66	0.50	0.81	0.57
Lower Heating Values, GJ/tonne				
Primary Product	16.1	19.1	31.5	24.3
Final Product	41.5	39.6	41.7	39.6
(GASOLINE FRACTION)	(0.8)	(0.9)	(0.7)	(0.9)
Energy Costs, US$/GJ				
Primary Product	9.32	6.91	13.44	12.27
Final Product	16.24	12.99	19.54	14.77
Product Energy Value[1], US$/GJ				
Primary Product	6.70	6.70	5.20	5.20
Final Product	8.30	8.45	8.15	8.45
Product Cost/Value Ratio				
Primary Product	1.39	1.03	2.58	2.36
Final Product	1.96	1.54	2.40	1.75

[1] Average spot market price from 1977 to 1987 for comparable petroleum-based liquid fuel.

TABLE 5
COMPARISON OF PROCESS ENERGY EFFICIENCIES -
LOWER HEATING VALUES BASIS

- - W O O D - -

	AFP PRESENT	AFP POTENTIAL	LIPS PRESENT	LIPS POTENTIAL
Primary Liquefaction				
Feed to Liquid Product	0.62	0.69	0.59	0.51
Total Energy to Liquid Product	0.61	0.68	0.55	0.48
Total Energy to Products	0.61	0.68	0.55	0.48
Finished Product				
Feed to Liquid Product	0.57	0.55	0.55	0.53
Total Energy to Liquid Product	0.52	0.53	0.48	0.49
Total Energy to Products	0.52	0.53	0.48	0.49

Table 6. Feedstock Price Sensitivities

FEEDSTOCK PRICE SENSITIVITIES

US$/ton final product	Feedstock Price, US$/wet ton 0	10	20	30	45
Wood AFP Present	411	499	586	674	805
Wood AFP Potential	266	349	432	514	639
Wood LIPS Present	538	630	723	815	954
Wood LIPS Potential	324	411	498	585	715

Table 7. Capital Cost Sensitivities

CAPITAL COST SENSITIVITIES

US$/ton final product	Capital Cost (FCI), percent change -20	-10	0	10	20
Wood AFP Present	622	648	674	700	726
Wood AFP Potential	486	500	514	529	543
Wood LIPS Present	754	784	815	846	877
Wood LIPS Potential	553	569	585	600	616
Peat AFP Present	619	650	681	712	742
Peat AFP Potential	379	397	414	432	449

Figure 1. Process Schematic of Wood AFP - Present Technology

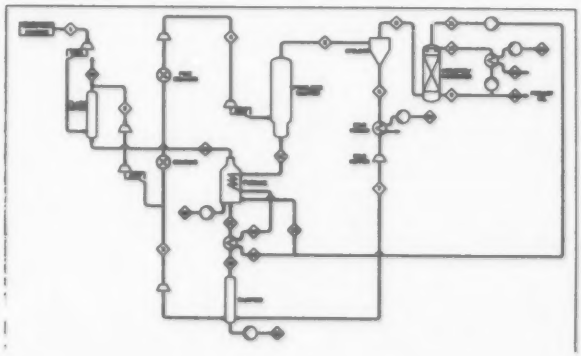


Figure 2. Upgrading AFP Primary Oil, Two-Stage Hydrotreating

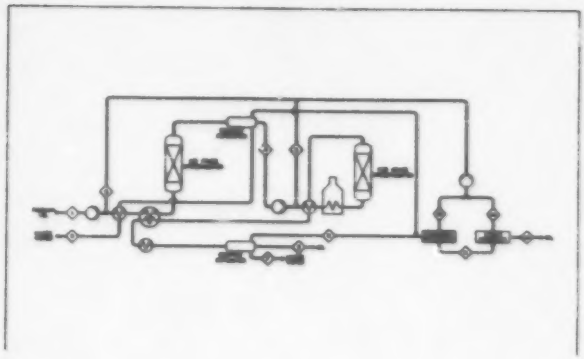


Figure 3. Process Schematic Wood AFP - Potential Technology

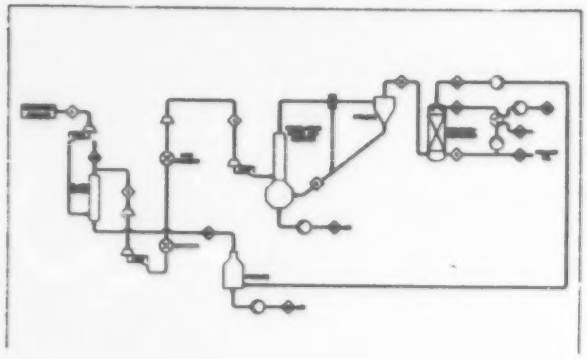


Figure 4. Nonisothermal Catalytic Hydrotreatment for Upgrading AFP Primary Oils - Potential Technology

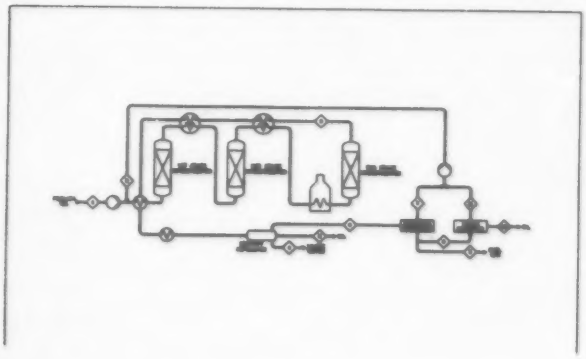


Figure 5. Process Schematic Wood LIPS - Present Technology

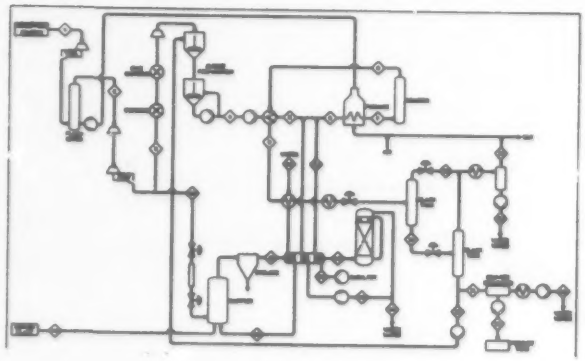


Figure 6. Upgrading Woods LIPS Primary Oil

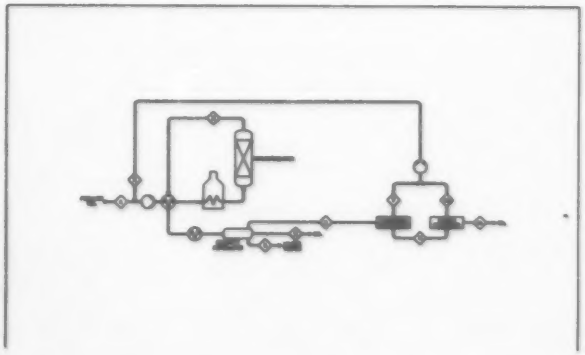
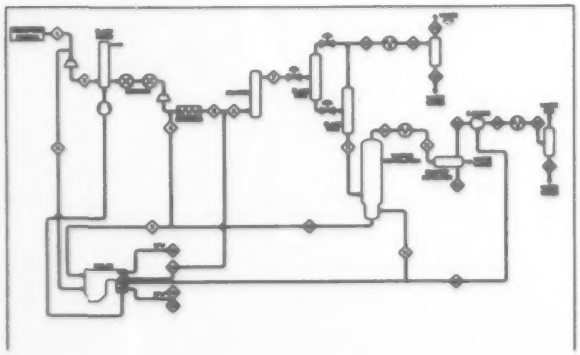


Figure 7. Process Schematic Woods LIPS - Potential Technology



THE IEA NETWORK ON BIOCONVERSION OF LIGNOCELLULOSICS*

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During the last three years two IEA projects, CPD 2 - Pretreatment of Lignocellulosics and CPD 5 - Conversion of C5 - Sugars to Ethanol were combined into Task IV - Bioconversion of Lignocellulosics. Two workshops were held, the first in Graz, Austria in 1986 and the second in Ottawa, Canada in 1988. Round robin tests on the chemical analysis of pretreated lignocellulosic substrates and the enzymatic hydrolysis of these substrates were carried out by the network participants. Various economic models were presented to determine the technoeconomic factors influencing the commercial viability of a bioconversion process.

Au cours des trois dernières années, la fusion de deux projets de l'Agence internationale de l'énergie, soit le CPD 2 (prétraitement de la lignocellulose) et CPD 5 (conversion du pentose en éthanol) a résulté en la création du projet IV (bioconversion de la lignocellulose). Dans le cadre de deux ateliers de travail tenus en 1986 à Graz en Australie et en 1988 à Ottawa au Canada, les paricipants ont procédé à un ensemble de tests sur les analyses chimiques de substrats lignocellulosiques eu présentation de différents modèles économiques afin de déterminer les facteurs techno-économiques pouvant influencer la viabilité d'un procédé de bioconversion.

INTRODUCTION

The IEA subgroup, Task IV - Bioconversion of Lignocellulosics was initiated in January 1987 and was formed from an amalgamation of the former CPD 2 - Pretreatment of Lignocellulosics and CPD 5 - Conversion of C5 - Sugars to ethanol group. The "evolution" of Task IV activities are indicated in Figure 1. The participating researchers first met at the Forest Research Institute, Rotorua, New Zealand in March 1985. At that meeting they agreed on a program of work which covered; Lignocellulose bioconversion and related projects; characterisation and quantification of untreated and pretreated lignocellulosic substrates; cellulase assays, production, adsorption and recycle; and process economics and equipment. They agreed to regular communication and exchange of data using the computer conferencing facility, COSY, which was based at the University of Guelph, Canada, as well as regular face-to-face meetings.

During 1986-88 there has been excellent cooperation between the participating laboratories. The participating labs are indicated in Table 1. Although virtually none of the participants received any financial support from IEA they expended a great deal of time and effort in both the analysis and exchange of data and in communicating their views to the other participants. A summation of this work is included in the three conference proceedings which were held in Rotorua[1], Graz[2] and Ottawa[3]. To encourage free and open discussion it was agreed, at these meetings, that papers in the proceedings could only be cited or copied with the permission of the authors. The use of the COSY computer conference has been cyclical, usually picking-up several months before and after a conference and while a round robin comparison is underway. There has, however, been regular use of the COSY system between individual labs.

At the Graz meeting, held in June 1986, the program of work was amended to more closely represent the research which was likely to be undertaken by the participating laboratories. It was also recognized that there was a need for some economic analysis of the various process steps as this area was conspicuously absent from any of the discussions. The participants agreed that companies trying to commercialize equipment or processes in this area should be invited to make presentations at the Ottawa meeting. Several industrial companies from IEA member countries attended this meeting and a full day was spent

[1] This paper will also be published in a special issue of "Biomass" containing descriptions of all the IEA sponsored networks in renewable energy.

discussing process economics. It was proposed that the various economic models could be used as a means of identifying the technical "bottle-necks" which could be addressed by the network participants.

As one of the obvious benefits of having participants from around the world was the ability to carry out comparative assays, a considerable amount of time was spent assessing standard enzymes and substrates. This activity was led by Hermann Esterbauer at the University of Graz. A summation of some of this work has been published earlier.[4]

In the results and discussion we have described the main achievements of the network during 1986-88. These include round robin comparisons in the areas of pretreatment characterization and enzymatic hydrolysis, and the ongoing discussions which peaked at the Graz and Ottawa meetings.

RESULTS AND DISCUSSION

At the Rotorua meeting held in March 1985 it was agreed that a second meeting should be held at Graz, Austria in June 1986. The symposium sessions at the Graz meeting covered pretreatment, analytical methods, enzyme technology, acid hydrolysis and a workshop on the conversion of C-5 sugars. The meeting highlighted two of the main cooperative projects which had been undertaken by the network. The first involved a round robin assessment involving the characterization and quantification of lignocellulosic substrates.

Prior to the Graz meeting four standard substrates, including a softwood, two hardwoods and wheat straw were distributed to each of the participating laboratories. The laboratories involved in this round robin comparison are listed in Table 1. The intent was to compare the analysis of these standard substrates and collate the values at the Graz meeting. Some of the values obtained by the various labs are included in the proceedings of the Graz meeting[2] and are listed in Table 2.

This was a most successful exercise and highlighted several important points for consideration. It was apparent that there was considerable variation in the analytical data. This confirmed the usefulness of the exchange. Most variation occurred in the carbohydrate analytical data and reflected the difficulties associated with accurate quantification of reducing monosaccharides. The numerous ways in which results were calculated made the collation of results, on an identical basis, extremely difficult to resolve. A direct result was the participants were made aware of the numerous errors which apparently occur in reporting data. Klason lignin determination showed the least variation while carbohydrate analysis showed the greatest discrepancies. The origin and determination of hydrolysis loss factors (HLF's) was identified as a major obstacle in the successful comparison of results. It was apparent that yield data from biomass conversion studies should be treated with caution.

Each of these points provided a basis for the discussions developed in the Biochemical Working Group (BWG) which is part of the Voluntary Standards Project lead by Tom Milne from SERI. This project is described elsewhere in this issue. The BWG met for the first time at SERI, Denver, in 1987 and a second time at Forintek, Ottawa, in 1988. At the Ottawa meeting it was decided that two steam pretreated substrates, i.e. aspen and spruce would be distributed, and these would be used to compare the various groups' ability to hydrolyse this material.

At the Ottawa meeting fourteen labs agreed to participate in a further round robin comparison using pretreated spruce and aspen as the substrate. Uniform batches of this material were prepared and sent to each of the laboratories for comparative analysis. The main objective of this work was to compare each laboratory's ability to hydrolyse a pretreated substrate using a common commercial batch of enzyme and their own source of cellulase enzymes.

The second round robin comparison involved the use of enzymatic assays for determining pretreatment effectiveness with Hermann Esterbauer (University of Graz) as co-ordinator. A systematic attempt to establish a standard enzymatic assay was tackled. In early 1986 samples from a Celluclast preparation, kindly donated by Novo, were distributed and three of the participating laboratories assayed the hydrolytic activity of this enzyme preparation against their own samples of Sigmacell 50. The intent was to demonstrate the relationship between enzyme dosage and digestibility. The results were presented at the Graz meeting with maximum digestibility values of 62.8%, 62.5% and 61.3% obtained by each of the labs.

At the Graz meeting it was decided that samples for one batch of Sigmacell 50 would be distributed to all the participating labs to ensure uniformity of the standard substrate. This was done and the COSY computer network was used to compare the values obtained by the participating groups. This information has been collated by Hermann Esterbauer and has been published in an earlier issue of Biomass[4].

As good agreement was obtained using a standard, commercially available substrate it was decided, at the Ottawa meeting in June 1988, that hydrolysis of a softwood and a hardwood would also be assessed. Wood chips from Aspen and Spruce were steam treated, in the presence of SO_2, to ensure maximum recovery of sugars while enhancing the enzymatic hydrolysis of these substrates. These samples were prepared in late 1988 and will be distributed to the fourteen laboratories who indicated they would participate by January 1989. The participating laboratories are indicated in

Table 3. The COSY computer network will be used by the participants to compare and collate the values. This comparison will form the basis for one of the sessions in the next Network meeting which will be held in Sweden in September 1989.

To try to build on the expertise and interest of the participants the major project areas covered by the network in the time between the Graz and the Ottawa meetings were pretreatment, enzymatic hydrolysis, process products and process economics. As a separate IEA sponsored initiative on standards had been initiated during 1987, those aspects of the network previously covered under analytical methods were restructured as the Biochemical standards component of this new task force.

As all of the participating laboratories felt that the activity could benefit from industrial participation and some detailed process economics, several companies from IEA member countries were invited to attend the Ottawa meeting. These groups gave presentations in the pretreatment, hydrolysis and process economics sessions and participated fully in all discussions. The various economic models, which described integrated bioconversion processes, indicated the complexity of any proposed plant which would convert lignocellulosic residues into fuels and chemicals. These economic models gave rise to considerable debate because of the many technical assumptions that had to be made. It was proposed that a discussion of these assumptions could identify the areas which required further research to clarify the issues. This will be one of the future activities of the network over the next two years.

Discussions conducted over the computer conference and at the two meetings indicated that a variety of products would have to be marketed to ensure the commercial feasibility of a bioconversion plant. Several options were discussed at the Ottawa meeting in the process products session. These included lignin fractionation and applications, ethanol production from both five and six carbon sugars and the other credits that could be obtained by selling various by-products.

The closing session of the Ottawa meeting discussed ways of maximizing the benefit of having an extremely cooperative group of research laboratories from about ten different countries. As one of the main successes of the network was in the comparison of pretreatment and assay methods it was agreed to continue this work. Pretreated samples have been sent out to all the participants and this material will form the basis of comparative enzyme and analytical assays. It was proposed that the various economic models presented at the Ottawa meeting could form the basis for a sub-group assessing process economics. The participants recognized that this might prove difficult to carry out because of various socio-economic factors which influence the construction and operation of a plant in various countries. It was also recognized that this was also one of the strengths of the network as it identified the different types of assumptions that were made in the various national programs.

The network intends to continue to use both the COSY computer conferencing facilities and regular face-to-face meetings to ensure good collaboration between the participating laboratories in the various countries. The participants agreed to continue comparative projects as a means of maximizing the interaction between the various groups and to move closer to areas crucial to the commercialization of a bioconversion plant.

CONCLUSIONS

The IEA Biomass Conversion Annex IV has provided an excellent forum for the laboratories from the participating countries. The success of the network can be measured by the attendance at the meetings and the excellent rapport that has evolved during the collaborative round robin comparisons. These round robin assessments and regular face-to-face meetings of the participants are essential to the success of the network. This is reflected in the predominant use of the COSY computer conference system before IEA sponsored symposia and during round robin comparisons. The program has steadily evolved from primarily addressing technical problems such as analytical procedures and pretreatment conditions to assessing equipment and economic considerations influencing the economic feasibility of a bioconversion plant.

The success of the activity can be demonstrated by the quality of the symposium proceedings and the results from the round robin comparisons. The main accomplishment of the network has been to encourage an international group of researchers with relatively diverse expertise to develop an excellent rapport and work on a common objective. It is expected that this group, with the addition of participants from countries which have recently joined this IEA activity, will continue to build on this camaraderie and evolve a program which represents the sum of their own individual programs.

Acknowledgements

It is impossible to list all of the individuals who have made this activity a success as the program has depended on the involvement of all the participants. We would however like to acknowledge the support and guidance we have received from R.D. Hayes and D. Stevens throughout this activity. H. Esterbauer and W. Steiner have been a major force behind all of the round robin tests which have formed the basis of the network cooperation. The Graz based participants also coordinated the successful Graz meeting. The authors would like to thank their own

organizations, Forintek Canada Corp. and the Forest Research Institute for their support in providing the resources for two of the network symposia. We would also like to thank our colleagues for all their work related to these meetings and throughout the activity.

All of the participating laboratories invested a great deal of their own time and resources in this activity. Any success was due to the work of all the participants.

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2. Proceedings of the Symposium on the Pretreatment of Lignocellulosic Materials. June, 1986, Graz, Austria. 410 p.

3. Proceedings of the Workshop on the Bioconversion of Lignocellulosics. June, 1988, Ottawa, Canada 125p.

4. The Results of a Round Robin Test for the Evaluation of Enzymatic Digestibility. Esterbauer, H., Steiner, W. and Sattler, W. (1989) Biomass 16 pp.

Figure 1: The evolution of Task IV "Bi conversion of Lignocellulosics"

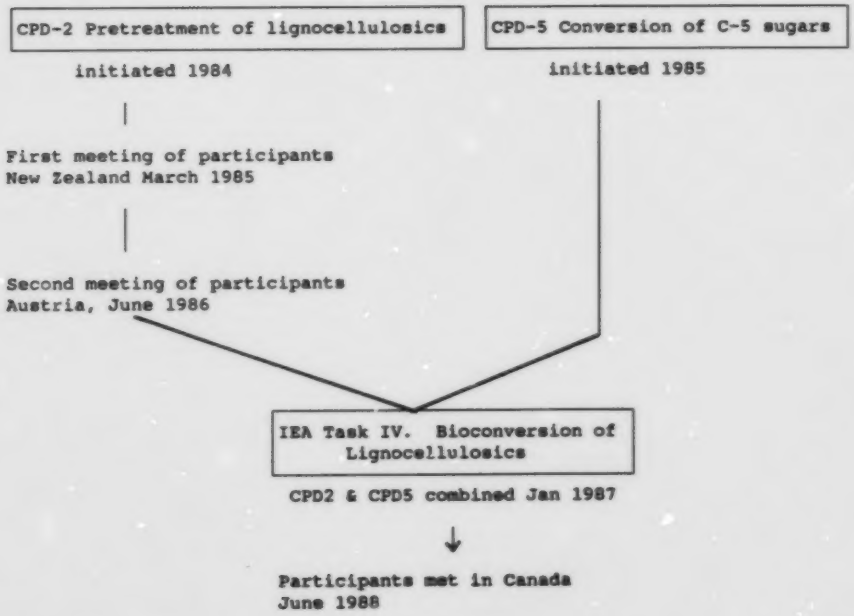

Table 1. Laboratories participating in the round robin comparison of lignocellulosic substrate analyses

Laboratory	Country
Forest Research Institute, Rotorua	New Zealand
University of Graz, Graz	Austria
Solar Energy Research Institute, Golden	U.S.A.
BFH Inst. Wood Chemistry, Hamburg	Germany
Swedish Pulp and Paper Res. Inst., Stockholm	Sweden
University of Lund, Lund	Sweden
Forintek Canada Corp., Ottawa	Canada
Ruakua Agricultural Research Centre, Hamilton	New Zealand
Inst. Francais du Petrole, Rueil-Malmaison	France
CSIRO, Clayton	Australia
University of Innsbruck, Innsbruck	Austria
Mississippi State University	U.S.A.

Table 2. Comparative analysis of *P. deltoides*, original wood basis, as a percentage of oven dried material before solvent extraction.

Laboratory	Extractives	Ash	Klason lignin	Acid-soluble lignin	Glucan	Xylan	Mannan	Arabinan	Galactan	Rhamnan	Total carbohy-drate	Uronic acid	Sum reported values
A	2.48	0.62	21.54	3.16	42.07	17.58	2.86	NR	1.25	NR	62.51	NR	90.31
B	4.30	0.41	22.30	NR	38.20	12.0	0.0	0.0	0.5	NR	51.45	3.0	81.46
C	2.5	0.5	22.0	NR	44.0	13.7	2.8	<0.3	0.75	NR	61.0	NR	86.0
D	5.0	0.3	20.54	NR	42.11	14.88	3.11	NR	0.50	0.38	61.23	NR	87.87
E	0.52	0.49	23.68	2.59	42.38	NR	3.48	0.99	0.5	NR	69.73	NR	97.01
F	4.0	NR	25.0	NR	38.1	14.8	2.9	0.7	0.6	NR	57.0	NR	81.0
G	2.90	0.49	22.45	NR	42.8	14.22	2.10	0.10	NR	NR	59.82	NR	95.65
H	2.37	0.55	21.84	2.81	NR	NR	NR	NR	NR	NR	63.16	NR	90.75
I	NR[3]	0.44	21.85	NR	45.31	14.34	3.44[2]	0.38	NR	0.29	63.76	0.39	86.44
MEAN (s.d)[1]	3.11 (1.58)	0.48 (0.10)	21.80 (1.14)	2.85 (0.29)	NR (2.56)	45.31 (1.67)	14.34 (1.16)	0.43 (0.41)	0.68 (0.29)	0.34 (0.06)	61.07 (4.99)	1.70 (1.85)	

[1] Standard deviation

[2] One value reported for galactan and mannan (values not included in mean)

[3] NR - not reported

Table 3. Laboratories participating in the enzymatic assessment of the effectiveness of pretreating a hardwood and a softwood

Laboratory	Country
University of Graz, Graz	Austria
University of Waterloo, Ontario	Canada
NRCC, Div. of Biosciences, Ontario	Canada
Iogen, Ontario	Canada
Forintek Canada Corp., Ontario	Canada
Morris Wayman Ltd. Consultants, Ontario	Canada
VTT Biotechnical Lab., Espoo	Finland
Inst Francais du Petrole, Rueil-Malmaison	France
BFH Inst. Wood Chemistry, Hamburg	Germany
Forest Research Institute, Rotorua	New Zealand
Chemical Centre, Dept. Appl. Microb., Lund	Sweden
Swedish Pulp and Paper Res. Inst., Stockholm	Sweden
Cook College, Rutgers University, New Jersey	USA
Michigan Biotechnical Institute, Michigan	USA
Solar Energy Res. Inst., Colorado	USA

THE BIOMASS PRODUCTION TASK OF THE INTERNATIONAL ENERGY AGENCY BIOENERGY AGREEMENT

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INTRODUCTION

The International Energy Agency's Bioenergy Agreement (IEA/BA) encourages cooperative, international research and development work (R&D) on biomass for energy in three areas: biomass growth and production technology in short rotation forestry, biomass from conventional forestry and conversion. Thirteen countries participate in this work at present: Austria, Belgium, Canada, Denmark, Finland, Japan, Ireland, Italy, New Zealand, Norway, Sweden, U.K. and U.S.A. Countries may participate in those R&D Tasks which serve their national interests.

The Forestry Energy Agreement, the forerunner of the IEA/BA, was initiated in 1978 by Canada, Ireland, Sweden and U.S.A. More countries joined, and in 1986 the work expanded to other areas of bioenergy.

In 1986, a three-year programme was initiated which is now being completed. In 1988, a follow-up of this programme was formulated for the period of 1989-91.

Both programmes are organized into Tasks, led by operating agents. Each Task has a Technical Advisory Committee with one member from participating countries. The R&D work in these Tasks is structured in Activities, each led by an outstanding scientist-expert and assisted by participants, scientists-experts from participating countries. A basic budget, securing scientific cooperation and coordination, is provided by participating countries.

THE 1986-88 PROGRAMME

The activities, leaders and participants of the 1986-88 programme in the area of biomass production are included in Table 1 (Zsuffa and Gambles 1987).

The Collection and Distribution of Poplar Species, Hybrids and Clones (Poplar Exchange) This activity has provided the participants with new hybrid progenies and clones resulting from the Belgian programme. Poplar seeds and cuttings have been gathered and distributed to participants for immediate use or for long-term breeding programmes. Testing is done with common designs and criteria, including testing for local pathogens. Information feedback provides a better understanding of clonal reaction to various diseases in different environments (Steenackers *et al.* 1989).

Evaluation of Alnus Species and Hybrids (Alder Evaluation) Earlier cooperative projects distributed alder seed and engaged in breeding the species. Collections and hybrids resulting from this work have been evaluated in provenance/progeny trials according to a common design in participating countries. The tests in each region will detect geographic trends and genotype-environment (GXE) interactions. The suitability of species, provenances and hybrids for future tree improvement will be determined (Hall and Burgess 1989).

Hybridization, Clonal Selection and Distribution of Salix Clones (Willow Breeding) Numerous species and clones of willows were collected and distributed in an earlier cooperative project. Phenotypes and hybrids produced from these collections have been exchanged and their performance evaluated. Information on methodology and breeding results, including disease surveys and breeding for resistance, is exchanged. Superior clones for testing and use in biomass plantations are being distributed (Zsuffa 1989).

Development of Methods for Exchanging Genetic Evaluation Data (Joint Evaluation) Test plantations of poplar, willow and alder were established in an earlier project according to standardized designs. Data have been collected on growth,

phenology, and pathogen problems, as well as climatic and soil conditions. Data is pooled and analyzed for information on GXE effects, environmental differences between plantations and clone/family stability (Ager *et al.* 1989).

Cell, Protoplast and Tissue Culture of Short Rotation Species (Cell Culture) During the formulation of the programme of work for this Agreement, it was recognized that biotechnology would play an important role in increasing biomass production. In this project, information is exchanged on callogenesis requirements of the species for different sources of explant material. Catalogues of institutions, scientists and projects have been assembled to facilitate communication. A catalogue of form-trees is also being collected as a first step in engineering of ideotype (model) trees (Cheliak and Klimaszewska 1989).

Development of Biotechnology Programmes for Energy Forestry (Biotechnology Development) A major factor affecting yield (and survival) in energy plantations is disease. It was agreed that there was an urgent need for the rapid development of disease resistance in plantation species and that biotechnology could effectively accelerate this process. Available biotechnological methods are employed to develop high yielding, disease-resistant poplar, willow and alder clones for energy plantations. Pathotoxicity factors for major diseases affecting these species and genetic factors of resistance are investigated (Hubbes 1989).

Nutrients and Growth Relations (Nutrients) Active research centres and their undertakings have been documented and a cooperative research strategy prepared. Water and nutrient relations are of concern. Common protocols for irrigation/fertilization are under development and validation, and an operational model on this topic is being tested. Existing models for short rotation forestry have been evaluated. Nutrient and water management guidelines will result from this work (Mitchell 1989).

Developing the Coppicing Potential of Selected Hardwoods (Coppice) Coppicing, a little-understood and very important aspect of short rotation forestry, was deemed to warrant further investigation. Physiological factors and management regimes of coppicing have been studied. The morphology of coppiced trees including bud development and root/shoot ratios is under study as are several physiological aspects. Cultural factors under review include cutting season and equipment, stump diameter and height, root pruning, rotation length and herbicide applications (Ferm and Kauppi 1989).

Production Technology An overview of currently available techniques and equipment to establish, manage and harvest short rotation forests has been prepared in the form of a "Source-book". All production functions involved have been examined to document current practices and to identify areas where cooperative R & D efforts need to be made (Christopherson and Mattson 1989).

Economic Evaluations for Short Rotation Biomass Production Systems (Economics) The purpose of this activity was to develop standardized methods for evaluating the economics of biomass production systems. The state-of-the-art in economic evaluation for short rotation systems has been assessed, and the procedures and practices that are commonly acceptable have been determined. The activity resulted in a compilation of available economic evaluation procedures and recommendations for increasing their resolution (Lothner 1989).

The results of this unique cooperation are in development and exchange of superior stock, exchange of information, collaborative research and training, standardized procedures and evaluations, handbooks and manuals, joint evaluations, expert reports and recommendations. The participating countries use the results according to their own conditions and needs and, by doing so, utilize the resources and expertise of other countries participating in this programme.

THE 1989-1991 PROGRAMME

The current three year programme expires in April, 1989 with participants deciding to continue with the cooperation. Planning has been underway, and the new 1989-91 programme in biomass production is entitled "Improvement of Energy Dedicated Biomass Production Systems". In this programme, which started in January, 1989, some of the present activities continue. Also, new projects have started such as the development of ideotype (model) trees for energy forestry, studies of feedstock qualities as related to conversion and the potential for improvement by biological and cultural means, and the production of agricultural and herbaceous crops for energy. The activities, leaders and participants of this programme are included in Table 2.

Energy Forestry Production Systems The aim of this activity is to develop, refine and improve biomass production

systems for short rotation energy plantations. The activity deals with energy forestry plantation systems for hardwoods and conifers. Criteria for choice of site and species will be reviewed. Cultural techniques involving site preparation, planting, weed control, fertilization, irrigation and harvesting are main issues, along with environmental aspects, within this activity. There is a need to present an overview of the currently available knowledge for those issues. Previous research has shown that weed control during the establishment phase, and spacing - harvesting cycle relations are of utmost importance for plantations on a practical scale. These questions will be addressed at the first workshop of the activity in 1989.

The production technology sourcebook, prepared earlier, will be kept updated and provide information for a future expert system.

Energy Forestry Ecophysiology The aim of this activity is to better understand the processes determining tree growth under short rotation intensive culture. The work programme includes: (a) documentation of interrelationships of species (clone)-site interaction, (b) investigation of stand dynamics, (c) investigation of water and nutrient relations, (d) investigation of factors determining coppicing ability in candidate species, (e) investigation of growth of short rotation plantations with respect to abiotic factors. The work of the activity will be conducted through a programme of commissioned review/state-of-the-art reports, seminars and workshops on each of the main themes.

Dedicated Agricultural/Herbaceous Crop Systems This activity will focus on agricultural/herbaceous energy crops and cropping systems. It will emphasize crop production from a perspective that includes factors related to integrating production with conversion and end use. A major goal is to identify and assess ways that improvements in energy crop production can improve the overall viability of biomass-based fuel cycles. In promoting information exchange among participating countries, the activity will use workshops, collaborative reviews, and state-of-the-art reports.

Pest/Disease Management The aim is to: (a) collect and exchange information on prevalence, severity, epidemiology and control of pests and diseases in short rotation plantations and on host resistance mechanisms, (b) carry out international surveys of diseases and pests, assess damage potential and advise on control, and (c) stimulate research collaboration. The coordination of pest management and surveys will be done according to continents (Europe and North America), while the studies in epidemiology and resistance mechanisms will be done by corresponding experts.

Wood Feedstock Qualities The aim of this activity is to increase the state of knowledge of wood feedstock qualities as related to the possibility of biological management and improvement and to promote communication and cooperation with researchers in conversion technologies. A literature review on this topic has been completed. A compendium of current and proposed research projects on wood biomass qualities will be prepared to identify the state of knowledge. A joint meeting of biomass production and processing/ conversion researchers-experts will be held to determine which feedstock qualities are most desirable and which can be selected or manipulated in the species under study. The possibility of preparing a wood feedstock quality sourcebook will be considered. Cooperative R&D will be initiated on feedstock quality determination and control, especially species/clone variation and manipulation.

Tree Ideotype The aim of this activity is to define ideotype (model) tree traits for energy-dedicated production systems. Important steps in this project are to: (a) assess ongoing and potential breeding and biotechnology programmes related to ideotype tree development in participating countries and determine involvement in the activity, (b) characterize biomass plantation systems and describe ideotype trees for each system/species, (c) catalogue and characterize existing genetic stock and data related to ideotype tree traits, (d) assess genetic control of ideotype traits and identify genetic markers by analyzing existing trials and data, (e) select most feasible and significant ideotype traits for improvement by modelling and computer simulations, and (f) stimulate research and development work in ideotypes using advanced breeding technology and biotechnology.

Exchange of Genetic Material The aim is to facilitate the exchange of stock amongst participants and to carry out screening programmes. The programme of work includes exchange of poplars and willows, advising participants on a regular basis of the stock available for exchange, determining national restrictions on exchange, and making available reasonable amounts of stock for exchange. Screening of exchanged stock for pathogens will be done with identical sets of clones as controls. Poplar screening for bacterial canker and

Melampsora rust will be done in Europe (Belgium) and for *Septoria* canker and *Melampsora* rust in North America (Canada). Willow screening for *Melampsora* rust and cankers (*Xanthomonas* and/or *Glomerella*) will be done in Europe (Sweden) and for *Melampsora* rust and *Glomerella* canker in North America (Canada).

Joint Trials The aims are to: (a) continue the measurement, analysis and use of results from the joint evaluation trials established under previous projects of the group, (b) update catalogues of new materials for testing and establish a source of supply of standard entries for all genetic tests to permit cross-referencing between studies, (c) coordinate the establishment of new tests in member countries using standard entries and the new material of most interest in each country, and (d) maintain a directory of researchers and a bibliography of literature on genetic improvement. In 1989, a workshop will be held to bring everyone up-to-date on the status of the trials established in earlier years and to agree on any necessary modifications in measurement and analysis techniques. Two trial coordinators, one for Europe and one for North America, will visit each trial and participating organization at least once each year to ensure continuity and consistency in the maintenance and measurement of trials. An annual summary of results and interpretations will be published and distributed to the participants.

SOME RESULTS OF THE IEA/BA COOPERATION ON BIOMASS PRODUCTION

In the developing world, there are several international cooperative research and development projects in forestry supported by the Food and Agricultural Organization (FAO) of the United Nations and various other international and national aid agencies. In the developed industrialized world, there are few international and financially supported programmes in forestry. IUFRO is a world-encompassing organization of forest research organizations but does not provide for any support of international research in the industrialized world. In Europe, the European Economic Community (EEC) programmes play such a role. However, transcontinentally, the IEA/BA programme is unique in supporting the development in a new field of agroforestry-biomass plantations.

The results of the R&D cooperation in biomass production sponsored by IEA/BA are also unique. These are in collection, exchange and joint evaluation of genotypes for planting stock, state-of-the-art reports on important aspects of biomass production, manuals and catalogues, and information exchange. All this has had a stimulating effect on R&D programmes in participating countries and in initiating research where gaps in knowledge existed. For example, willow breeding activities advanced considerably, now indicating new experimental clones of 40-50 odt/ha/yr yielding capacity (Gullberg 1989, Zsuffa 1989). Also, research in willow disease problems was initiated owing to IEA/BA cooperation and progresses with good prospects in resistance breeding. Included in this list of important achievements is the international standardization of methods for economic evaluation which facilitates the appraisal of the profitability of biomass production.

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TABLE 1

IEA/BA - TASK II - BIOMASS PRODUCTION
ACTIVITY LEADERS AND COUNTRY PARTICIPATION

	BELGIUM	CANADA	FINLAND	IRELAND	SWEDEN	U.K.	U.S.A.
POPLAR EXCHANGE	STEENACKERS*	X					X
ALDER EVALUATION	X	X				X	HALL*
WILLOW BREEDING	X	ZSUFFA*	X	X	X	X	X
JOINT EVALUATION		X			LEDIN*		X
CELL CULTURE		CHELIAK*			X		X
BIOTECHNOLOGY DEVELOPMENT		HUBBES*	X		X		X
NUTRIENTS		X			X	MITCHELL*	X
COPPICE		X	FERM*		X	X	X
PRODUCTION TECHNOLOGY		X			X	X	MATTSON*
ECONOMICS		X		X		X	LOTHNER*

* ACTIVITY LEADER
X COUNTRY PARTICIPATION

TABLE 2

IEA/BA Task 5 - Biomass Production Systems

Activity Leaders and Country Participation

Activity	Austria	Belgium	Canada	Denmark	Finland	Italy	Norway	Sweden	UK	USA
Production Systems	x		x	x		x		Ledin*	x	x
Ecophysiology			x		x	x		x	Mitchell*	x
Agricultural/Herbaceous	x					x				Cushman*
Pest/disease		x	x					x	Royle*	x
Feedstock			Zsuffa*					x	x	x
Ideotype			x		Koski*			x	x	x
Exchange		Steenackers*	x		x			x	x	x
Trials		x	x				x	x	x	Nell*

INTRODUCTORY REMARKS
SESSION IV - COMMERCIALIZATION AND TECHNOLOGY TRANSFER
SEVENTH CANADIAN BIOENERGY R&D SEMINAR

C.R. CUPP

PARTEQ Research and Development Innovations
Queen's University

We all know we live in a delicate environment and, with it, fragile economic circumstances. If we need to be reminded, a glimpse of recent newspaper headlines is enough to illustrate our precarious situation both environmentally and economically (Figure 1). The price of gasoline at the pump has already jumped in the U.S. Thus, we are about to learn again the critical importance of sustainable energy sources.

Two years ago, at the sixth seminar in this series, I remarked that most of our political and economic institutions are designed only to cope with current problems. When problems have not yet reached a crisis stage, no one pays any attention to them. Efforts to resolve long-term problems come about almost entirely as a reaction to crisis.

Unfortunately, once a crisis has passed, one reverts to past ways. Learning from experience is a faculty almost never practised! It does not take great wisdom to say that petroleum will become more costly as greater efforts are required to find and extract it. But we do need to be constantly reminded of that fact. World demand for energy will grow, and bioenergy will only supply a part of the demand growth.

As I prepared these notes, the first shoe, the throne sppech, had dropped. After we meet, the second shoe, the budget, will have landed with a thud. The infamous deficit looms large. The government now declares that "reducing the deficit is a vital necessity if Canada's economic well-being is to be secured." The government also flattered Canadians for "having a unique sense of their relationship to the land" and for being "confident of their abilities to compete successfully in the international economy of a widening world."

If we are to deal effectively with the problems of environmental pollution and our competitive position in the global economy at the same time, we **must** develop a long-term, consistently-supported renewable energy program. Figures 2-5 show that federal program expenditures on renewable energy have been anything but consistent, and have been thinly spread. In the current issue of GEOS, a publication of EMR, Stephen Bolcso reports that the renewable energy **and** generic environment R&D program of the federal government, now known as Task 4, will use less than $12 million this year. The bioenergy portion of that will be only $6 million.

Despite the roller-coaster funding over the past decade, and despite thinly-spread resources, valuable R&D has been done in Canada, and we must now focus on the problem of marketing renewable energy technologies.

A report by Eric Bevan to the Commission of European Communities notes that, "although the world oil market still remains volatile, traditional market forces have to a large extent been re-established and renewables find themselves being judged less on their long term potential as contributors to diversification and more on short to medium term economic criteria in competition with well established conventional sources. Renewables now have to prove themselves, without subsidy, in the harsh reality of the commercial market where capital cost, technical performance, reliability and returns on investment have to measure up to prevailing requirements." In other words, the crisis has passed, long live the fossils!

Renewables must penetrate complex markets where technologies are well established and supply networks exist. Some renewables tend to be intermittent and dilute in energy content, so demand a whole new business structure if they are to be exploited on any substantial scale. We must accept the fact that there is an inherent market reluctance to adopt <u>any</u> new technology, and an additional scepticism about energy technologies.

For renewables to succeed; they must appear to be sound investments; they must at least match current technologies in terms of cost, reliability and convenience; and, they must have an acceptable environmental impact.

In recent months, funds have been withdrawn for demonstration projects. Without making a judgment on the effectiveness or organization of the past programs, it seems clear to me that demonstration projects are a necessary component of the technology transfer spectrum. It is the link between the R&D phase and the later investment phase. Demonstration projects are operated on an industrial scale and must have prospects of economic success, yet differ from the investment stage in that the inherent risks are too high for most entrepreneurs. Thus, it is not likely that commercial interests will commit the necessary financial and human resources to demonstration projects. It follows that substantial government funds will continue to be required to support demonstrations, disseminate the results, and encourage industry, especially consortia, to adopt the technology.

Greater effort is needed in the EMR program to "market" the results of successful demonstration projects.

Why have we not seen greater adoption of renewables technology? There have been a number of near-successes, some bankruptcies, a few successes. Although it is not especially the Canadian way, should there not be an amalgamation of the renewable energy interests of several companies to form consortia for the commercialization of renewable energy technologies?

Perhaps in the final sessions of this seminar, we could consider this further.

Let us now hear firsthand how three groups have conducted their technology transfer programs.

FIGURE 1

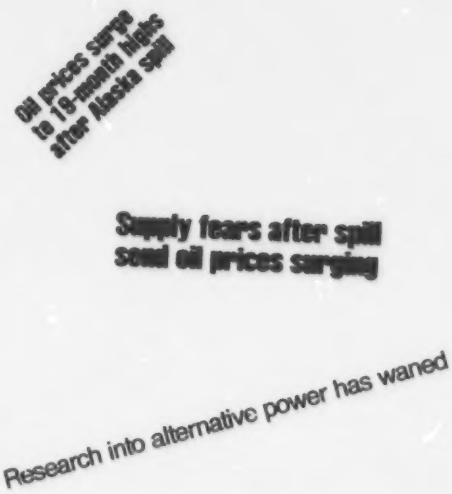


FIGURE 2

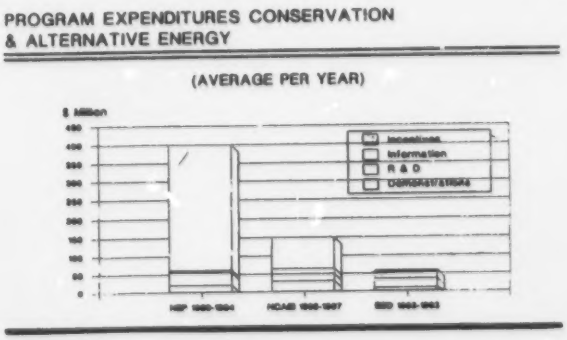


FIGURE 3

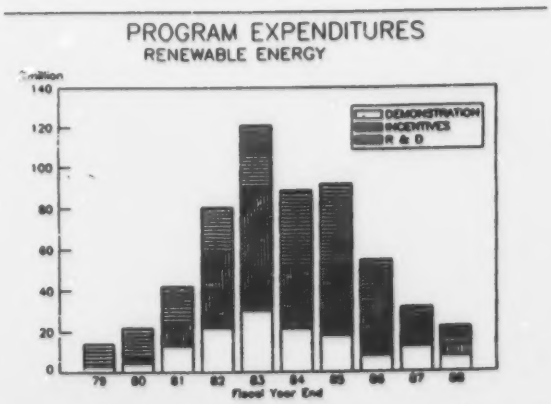


FIGURE 4

ESTIMATED FEDERAL BIOENERGY
R & D EXPENDITURES

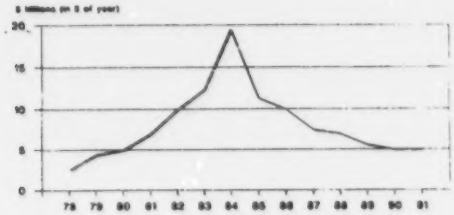
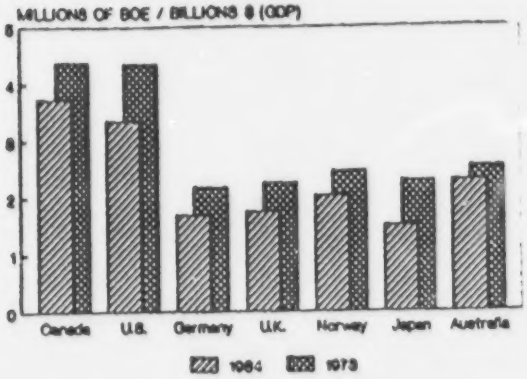


FIGURE 5

FINAL ENERGY CONSUMPTION / GDP
(bbl of oil equivalent /GDP ($US 1980))
1973 and 1984



STRATEGIES IN COMMERCIALIZING SCIENTIFIC DEVELOPMENTS

John Unsworth, B.A., LL.B.

Petro Tire Inc., Hamilton, Ontario

I have had the opportunity of participating in the start-up of numerous advanced technology companies in the biotechnology industry, computer hardware and software industry and most recently, the recycling industry.

BioFrost Inc., a subsidiary of Advanced Genetic Sciences, Inc. (now DNA Plant Technologies Inc.) scaled-up the production of SNOMAX, an ice nucleating bacteria used to enhance the production of artificial snow for ski hills. This material was used at the 1988 Winter Olympics in Calgary and is now produced by Kodak under license. It is now used in many countries around the world. BioFrost used the facilities of the Alberta Research Council to develop a commercial method of producing the bacteria. BioFrost was also responsible for Canadian regulatory compliance for FROSTBAN, the first genetically engineered organism to be tested in the open environment.

While President of HYPERCUBE INC. I participated in the transition of a computer software\hardware company from a company operating out of a professor's laboratory at Waterloo University, to a company producing both hardware and software for the North American market. The molecular modeling software was designed specifically for advanced parallel computers. While the software will run on Intel's parallel computer, it also runs on HYPERCUBE's transputer based parallel computers. HYPERCUBE is now expanding greatly its marketing and scientific capabilities. Certainly parallel computing is the wave of the future in advanced computation and this Canadian company will form a very important building block in establishing a domestic computer industry for tomorrow.

Most recently I have been involved in the organization of the Vacuum Pyrolysis Project initiated by Professor Christian Roy at the University of Laval. Petro-Tire Inc. of which I am the President is now preparing to design and upgrade the existing pilot plant facility into a demonstration plant in cooperation with UltraMar, Laval University and various Government agencies. This plant will have a capacity 1\10th that of the production plant and will incorporate an advanced heat exchanger and carbon-black upgrading unit.

The importance of the vacuum pyrolysis technology extends beyond tire recycling. It has applications in the production of fine chemicals as well as the treatment of oil sludges and municipal wastes. The development of all these uses will benefit from the lessons learned in the tire recycling plant.

Tire recycling has become a necessity because of the huge piles of tires which represent a significant environmental risk. Each year, 20 million tires in Canada and over 300 million in the U.S. are disposed of. While some of these tires are recapped or ground up for special uses, most are simply dumped in rural farmland or in landfill sites. When buried in landfills they eventually float to the surface, and if piled will cause serious harm if ignited by lightning or vandals. However, the tires also represent a source of energy and raw products for the production of rubber parts. The vacuum pyrolysis process converts the tire into approximately 55% oil, 27% carbon black, 10% steel, 5% gas and 3% ash. All of these materials can be sold. The oil is usually used as refinery feed stock, while the carbon black is used to make rubber parts. The high quality steel is sold for scrap and the ash is used for building materials.

One of the most important features of the technology is that the reduction of the tires is completely enclosed, avoiding pollutants. By comparison, incineration facilities, even with

expensive scrubbers and bag houses, release pollutants, most notably nitrogen oxide, into the atmosphere.

Now I would like to touch on a number of subjects which I think are important in the commercialization of scientific developments. There is not enough time to detail the subjects involved; but I shall try to touch on those which I think are essential.

ASSESSMENT

Competitive Advantage

The first step is to understand what the scientific development is and how it relates to existing practice in the market place. Does the development give a sufficiently large competitive advantage that it is worth the effort to develop.

In order to develop a meaningful perspective, a full understanding of other available technologies is required and a sense of how these will develop over the time frame required to commercialize the target development.

Core Technologies

Another important consideration is whether the development is a core technology or merely a derivative. For example: vacuum pyrolysis can be viewed as seminal if one considers the many applications to which it can be put: tire recycling, energy utilization of biomass, municipal waste disposal and the treatment of petroleum wastes. The importance of this feature is not only that it makes the development more valuable if patent protection can be obtained; but also provides many routes of commercialization should one turn out to be less promising than expected. Also what is learned from the scale-up of one can be applied to the others. This creates great savings if a program can be implemented for the simultaneous commercialization of all these technologies. This is usually possible if the project is broken up into separate undertakings with different companies commercializing each technology. The forms these take can vary from joint ventures to licensing arrangements to outright sales of the intellectual property. A further advantage of a core technology is that the many possible paths of commercialization can be packaged and sold to support the further development of those with most promise.

There however lurks a danger in core technologies: Greed! The experience of the biotechnology industry is instructive. How many biotechnology companies came to grief because they were distracted by the vast possibilities and huge profit projections and consequently squandered their resources pursuing every new possibility.

Long Term Trends

The other thing to consider is the saying used by financial analysts — "The trend is your friend". Is the development in step with long term trends in the industry or is it a deviation which will have short term advantages? For example recycling of resources would seem to be in step with long term trends rather than short term conditions.

Proprietary Position

The importance of a proprietary position is generally of paramount importance, whether it be a patent or a trade secret. Care should be taken to ensure that the protection is real and the patent is strong and enforceable. One danger with patents is that they constrain decisions and assessments made during the course of the development. It is not unusual to see researchers persevere in trying to develop patentable features of a system when it would be better to take a new tack.

Financial Model

Perhaps the most important procedure is to create a financial model which will itemize all the variables which will effect the successful outcome of the project. This can be used to analyze the profit sensitivity to various factors. It will also give an indication of whether the economic payoff is sufficient to warrant the development costs. I have been amazed at how often this procedure is left until after the project is funded and takes on a life of its own. The financial model can also be used to generate cash flows for the scale-up and subsequent commercial operations of the company.

CAPITAL

Capital is a vital component of commercializing a scientific development.

Debt capitalization is usually not available to a start-up company because of the dearth of assets which can be pledged as security. Financial institutions do not like to lend on the security of intangibles. If the company however does have significant bankable assets this is an option which of course should be explored.

The raising of capital from investors is more complicated. It can take the form of a public offering in which there are rigorous regulatory requirements including registration, prospectus requirements, and continuing disclosure. Graphed on to these will be the requirements of the exchange on which the shares are traded. The exchange requirements are no less daunting and include capitalization requirements, disclosure and trading restrictions to name only three.

Most start-ups however utilize registration and prospectus exemptions of the applicable securities act. They do so to avoid the expense and delays of a public offering. For convenience I shall refer to the Ontario Securities Act, which is similar to those in other provinces.

There are many exemptions in the act but the principal ones are as follows:

Section 71(1)(d) as qualified by Regulation 19(e)(1). The Big Bucks Exemption.

This provision permits an investor investing a minimum of $150,000 in aggregate in the company. The amount of the investment attempts to limit this exemption to sophisticated investors who are capable of assessing the merits and risks of the investment.

However, this exemption, like the Seed Capital Exemption which follows, contains restrictions on the resale of the shares purchased. This feature limits the usefulness of this provision.

Section 71(1)(p) The "Seed Capital Exemption".

This exemption is available where the issuer solicits no more than 50 perspective purchasers resulting in sales to no more than 25 purchasers. The purchasers must purchase as individuals and must have access to substantially the same information as would be disclosed in a prospectus. If however an offering memorandum is provided it must be filed with the Commission (Reg. 21(4).

In addition the purchaser must be capable of evaluating the information provided or have it evaluated by a registered dealer or advisor.

There are other conditions for the applicability of this Section. Again the use of this exception is limited by restrictions on resale.

Regulation 14 (g) Exemptions for Government Incentives Securities

Generally, this exemption is available where the issuer solicits no more than 75 prospective purchasers resulting in sales to no more than 50. There must be an offering memorandum and the purchasers must be family relations or sophisticated investors who are capable of assessing the merits of the proposal.

The application of this Section includes:

a) Certain oil, gas or mineral exploration or development programs

b) Small Business Development Corporations

c) Certain scientific research companies.

Section 34 (2) and Section 72 (1) (a) Private Company Exemption

These Sections together exempt Private Companies from the Registration and Prospectus requirements of the Act. This is the most important exemption and should be considered carefully before shares are sold to investors.

A Private Company is defined as a company whose incorporating documents contain:

a) restrictions on the transfer of shares.

b) a limit of 50 shareholders

c) prohibition against any invitations to the public to subscribe for securities.

Of course the issuer cannot just recite these restrictions in the incorporating documents to qualify for the exemption; the issuer must actually satisfy the three requirements when issuing shares.

The most important test is whether the shares were issued to the public. The Pipegrass decision of the Alberta Court of Appeal established the test that to avoid a public offer, the purchaser must be a fried or associate of the Promoter or there must be a common bond, interest or association. The Ralston Purina decision of the U.S. Supreme Court described a purchaser who would not be a member of the public as one that can find for himself and need not know the information a prospectus would provide since he already has access to the information that the public would not.

These restrictions on the issuance of shares and the raising of equity capital are illustrative of the complexity of those provisions which restrict the raising of capital on equity markets. For most start-ups the Private Company Exemption is the only option available, but care must be exercised to be certain that its provisions are complied with.

Fortunately there are other methods of raising capital which do not trigger the Securities Act. Any method of generating early income will be as good as capital in properly financing the company. This can take many forms. Many biotechnology companies almost immediately engage in contract work. This contract work is chosen to complement or at least not interfere with the development work which forms the strategic path of the company. These contracts can provide vital cash flow.

Another method referred to above is to form joint ventures to develop derivative technologies or to license or sell them outright.

Strategic Partnerships also can serve a useful purpose here. Utilization of these is clearly seen in the computer software industry. Software start-ups often succeed in obtaining hardware at no cost from computer makers eager to have application software available for their machines. In some circumstances these hardware manufacturers will financially support these efforts and thus capitalize these companies. Another method used is to pre-sell the product. Where a company is eager to obtain a product and is willing to support its development it can sometimes be persuaded to prepay for it. this has the effect of capitalizing the company again.

In some cases licenses can be used to generate capital for development. The licensees can pay upfront fees payable immediately to support the continuing development of the technology. In the case of licenses it is vital that the licensees are bona fide developers and operators. Restrictions on assignment should be included in such transactions to ensure that these licenses are not construed as securities.

Another method of enhancing the capitalization of the company is to take advantage of government capital enhancement programs. These take many forms from cost sharing programs to outright grants. The programs are too numerous no mention here but some general comments should be mentioned. The difficulty with these programs is that the time required to apply for and then manage the contracts sometimes reduces their effectiveness. The familiar exclusion of overhead costs including administration costs is regrettable. Also the 50% cost sharing formula is not always sufficient to make a worthwhile risk affordable. This is especially the case for core technologies which are remote from commercial applications but from which many commercial products eventually will be produced, often by "Johnnys-come-lately".

MANAGEMENT

The commercialization of the scientific development often goes through a number of phases: laboratory, scale-up, demonstration, nascent production and finally mature production. Each of these steps requires different skills on the part of those managing it. Usually the laboratory stage is in the hands of a scientist. Later stages are managed by engineers, entrepreneurs and finally managers. It is even more complicated when the scientific development is made at a university and is commercialized by a company.

The importance of the company having control of the development from the scale-up through commercialization can not be overstated. The scientist who developed the technology in the laboratory and then patented the invention often has different and conflicting objectives to the company which wishes to commercialize it. The scientist usually operates in a non-directed line of inquiry which is best at uncovering novel systems. Unfortunately, at the scale-up stage, the company needs scientists and engineers who direct their efforts to achieve milestones in conformity with the business plan.

BUSINESS PLAN

I have left the business plan until last. We have all heard about how important the business plan is for the successful creation and operation of a start-up company. It is all true. The business plan serves many purposes. It is the corporate game plan. It describes the business, the competition, the business unity, goals and means of achieving them. It sets out a comprehensive financial plan with cash flow projections. Most importantly, it sets out a strategic path for the business.

Too often the business plan is prepared to raise capital and then is put away until the next round of financing. The business plan should be reviewed and updated regularly. It is a helpful tool to put in perspective changes in the direction of the company, to monitor progress against forecasts and to make short term activities conform to long term strategic objectives.

WORKING TOGETHER

Mr. Chairman no discussion of the strategies of commercializing scientific developments is complete without mentioning the need for the participants to work together to achieve a common goal. This is especially important now that companies are working together with scientists at universities and government laboratories, to develop products from fundamental scientific discoveries. Unfortunately success for scientists has depended upon personal achievement and personal recognition. Being perceived as the source of the idea and the discovery has been crucial to personal advancement in the academic world.

When these scientific developments are commercialized however personal recognition must give way to group cohesion and group achievement. I remember listing to a sage entrepreneur giving a talk at a conference and saying something I will always remember. He said that there is no limit to how far a man can go if he is willing to give the credit to others.

THE CHAPLEAU CO-GENERATION PROJECT
CLEAN ENERGY FROM WOOD WASTE

William P. Ivey, President

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Chapleau, Canada, P0M 1K0

INTRODUCTION

The Chapleau Co-Generation Project is a privately owned, operational 7 megawatt waste wood-fired cogeneration facility located in the heart of the Northern Ontario softwood lumber forest. This plant is a pilot project, the first of its kind in Canada, and was built to demonstrate the commercial feasibility of wood fired cogeneration. As a pioneer venture, this project is an ideal illustration of many aspects of the theme of this session: "Technology Transfer". In a way, this project has been a microcosm of the whole energy enterprise of this decade, involving nearly every area of current interest or concern: the environment; waste disposal problems; energy conservation; renewable resources; the electrical energy grid; and the economic climate.

During this present decade we have seen the growth of informed public concern over conservation of resources and the natural environment. We are also seeing a move away from large scale hydro-electric developments and nuclear power plants and an increase in the development and utilization of smaller energy resources. All of these trends and concerns are going to influence strongly how we go about creating new generation during the next decade. Energy from renewable biomass resources will become increasingly important in the future, and sooner or later, the concepts and technology which are the subject of our concern at this conference must be put into practice.

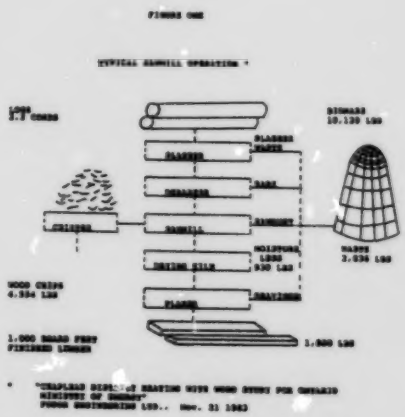
In this paper I hope to discuss some of these concerns and illustrate them by reference to the Chapleau Co-Generation Project.

THE NEED

Two fundamental needs are driving the energy from waste enterprise: the need to dispose of industrial and domestic waste without damaging the environment; and the need to reduce our dependence on non-renewable sources of energy. At the risk of sounding melodramatic, I would express these needs in even stronger terms, that is, as a society we can no longer afford to continue risking or harming our environment and wasting our resources as we have in the past. I don't claim that biomass fired cogeneration is going to solve all environmental and energy supply problems, but certainly the energy from waste approach is a step in the right direction.

Chapleau Co-Generation burns wood, which was probably mankind's first source of thermal energy. But our fuel is in fact the "garbage" of the lumber industry, and our plant is registered as a "waste disposal system". We receive and process the discharge from the waste belts of three local sawmills. This includes sawdust, bark, logs, and frequently large stones and scrap metal etc. Recently our plant manager gathered some of these rocks, and some large sprockets and drive chains which had jammed our fuel handling system, carried them over to a neighbouring sawmill, and confronted the mill foreman with "What's all this?". With a perfectly straight face the mill foreman replied "That's your fuel"!

Let's take a closer look at the wood waste situation by referring to Figure One.



To manufacture 1,000 board feet of finished lumber, a sawmill requires 2.2 cords of timber, a

biomass of 10,120 pounds (4,594 Kg). From this we derive 6,354 pounds (2,885 Kg) of useful product: 1800 pounds (817 Kg) of finished lumber and 4,554 pounds (2,068 Kg) of wood chips. There are nearly two and a half green tonnes of wasted biomass produced for every thousand board feet of finished lumber. Annual totals tend to become "mind-boggling".

Of course it is not all wasted. There are existing uses for sawmill waste: Sawmills generally burn sawdust or shavings for heating and kiln drying; pulp mills usually burn bark augmented with sawmill waste; and particle board production consumes some of this material. Yet in spite of present usuage, in Ontario alone we have over two million green tonnes of sawmill waste going to teepee burners or landfill sites every year.

Uncontrolled burning in teepee burners showers the countryside with fly ash; while landfill disposal can cause, and in some places has already caused, serious leachute problems, polluting lakes, streams and ground water. Moreover waste disposal costs add an additional financial burden to the already jeopardized economics of lumber production.

These and similiar considerations prompted the Ontario Ministry of Energy to commission a feasibility study for a district heating cogeneration project in Chapleau, a major lumber producing community of Northern Ontario. The resulting report entitled "Chapleau District Heating with Wood Study for Ontario Ministry of Energy" was circulated to potential developers, with the understanding of financial assistance to be provided both by the Ministry of Energy and the federal Department of Energy, Mines and Resources through their "FIRE" Program (Forest Industry Renewable Energy).

Foster Wheeler Limited, a major boiler manufacturer and engineering contractor with head office and manufacturing plant in St. Catherines, Ontario, rose to the challenge, and thus was born the Chapleau Co-Generation Project. Initially conceived as a district heating plant supplying community institutions, the a project concept changed when it became evident that district heating was not commercially viable. Increased lumber production also held promise of increased capacity, so the plant was ultimately sized to burn all the bark and sawdust wood waste that could be produced by full utilization of the lumber producing capacity of the Chapleau District, considered to be 110 million board feet annually.

THE OPPORTUNITY

Wood is a renewable fuel particularly important to Ontario, in fact to all of Canada, because the forest is the single greatest natural resource we have. The forest industry, and its derivatives, constitute the largest industry in the country. Wood fired cogeneration could ultimately become a significant component in our overall energy supply, so a unique opportunity exists at this time to develop "Chapleau type" cogeneration projects.

Although our plant is fueled entirely by sawmill waste, whole tree chips derived from the harvesting of otherwise commercially valueless species, or from forest management activities such as pre-commercial thinning is another possibility. Such "manufactured fuel", as we term it, is cleaner, easier to handle and has a higher thermal value than sawmill waste. Several projects fueled from whole tree wood chips are now on line or currently under construction, both in Canada and the United States.

The thermal generation of electricity is hardly a new idea, likewise the burning of sawmill waste isn't very original. What makes the Chapleau Co-Generation Project unique is that it is an independent, privately owned thermal generating plant buying and burning wood waste in order to sell steam to a private consumer and electricity to a major public utility. And, at bottom, the plant was built because it was intended to be a fair investment in its own right, and is being operated to produce a profit for the owners. To recyle the old cliche, "the bottom line is the bottom line".

Herein lies an opportunity for investors to participate in what is essentially a new industry in this country. This kind of development is good for the economy, because it mobilizes investment dollars, it generates work, during construction and creates permanent jobs for the next two or three decades.

THE CHALLENGE

Just before you all rush out to get your government grants and build your own cogeneration projects, may I temper your ardor by mentioning some of the more challenging, not to say problematic, aspect of cogeneration? There's good news and bad news; first the good news!

As I see it, cogeneration projects, as a commercial enterprise, tend to have two important advantages. Undeniably first in my mind is the matter of sales. The entire output of our plant has been sold for the next twenty years, an advantage enjoyed by few businesses. The purchasing utility's contractual obligation to purchase all energy produced by the parallel generator offsets some of the other risks inherent in this business.

The second advantage is that cogeneration in a large degree applies existing proven technology, so that in general there are no major research and development costs required for these plants. This is not to say that research and development is not required in the areas of combustion, pollution control and material handling, but turbine and generation technology is well established. The "bad news" as I see it, involves two aspects of cogeneration: scale, and fuel quality.

Energy from waste projects in general, and wood fired projects in particular are limited in scale, typically ranging from five to twenty megawatts, for the practical reason that the fuel supply tends to be scattered around the countryside. The economic hauling radius for any given project depends somewhat on the technical and economic parameters of that project, but ranges from thirty to about sixty miles. After all, one can only afford to haul "garbage" so far. I guess this limitation of scale really stems from the poor quality of "waste" fuels, so one might say that while the availability of the waste, or the need for its disposal, is the motivating force "fueling" the whole enterprise, most of the risks and costs in these projects arise from that same source. The fuel is our biggest assest and our biggest headache.

The limited size of the project limits revenues and profitability, and here lies the major technical challenge. A small cogeneration project must be carefully engineered to minimize capital and operating costs because the "economies of scale" are working against us. A seven megawatt cogeneration project has all the same basic ingredients as a seven hundred megawatt thermal generating station.

The smaller project not only needs the same basic pieces of machinery, i.e. fuel feed system, boiler, Turbine-Generator, condenser, etc., albeit on a smaller scale but also requires the same kind of "front end" project development in putting together all the technical, financial, and environmetal requirements.

Without taking the time to go into details, let me give you a sense of the overall scope of a project of this sort by referring to Figure Two, which I have optimistically entitled "THE INGREDIENTS OF A SUCCESSFUL COGENERATION PROJECT". This outline immediately highlights the fact that even a small 4 or 5 megawatt waste burning plant has to go through all the same project development and management exercises faced by a full-scale utility project. A saving grace is the fact that a small project such as ours tends to have little impact on the environment. Wood waste is a reatively clean burning fuel and particulate emissions are easily controlled. Thermal discharge is also of such a scale as to be readily controllable, and our plant performance has already demonstrated both these facts.

FIGURE TWO

INGREDIENTS OF A SUCCESSFUL CO-GENERATION PROJECT

1.	FUEL SUPPLY	A secure, adequate source of sawmill waste within an economic hauling distance.
2.	PLANT SIZE	Land, water, transmission line, road access, support community environmental impact.
3.	BUDGET DEVELOPMENT & FINANCIAL ANALYSIS	Design concept, capital cost start-up cost, operating cost revenue.
4.	FINANCING	Venture capital investment grant assistance, loan, lease, etc.
5.	ENGINEERING, PROCUREMENT & CONSTRUCTION	Site-building, water treatment, fuel handling, boiler, turbine-generator, cooling, controls & instrumentation, QA program.
6.	ENVIRONMENTAL & OPERATING PERMITS	Air and water Certificate of Approval, plant registration, Ontario Health & Safety Act, land use permits, insurance.
7.	PLANT STAFFING	Administration, operations, maintenance.
8.	COMMISSIONING	Start-up team, schedule, inspection, purchasing, turnover, run up, performance testing.
9.	THE END RESULT	Commercial operation.

However, to do all these things and still some up with a profitable project in the seven to ten megawatt range is indeed a challenge. Existing technology can be used, but the difficulty lies in configuring that technology in such a way that a project of this size can be profitable. The plant must be highly efficient and capable of being operated and maintained with a minimal staff. This requires the greatest degree of automation consistent with an acceptable capital cost.

The Chapleau Co-Generation Project is a working example of a plant that meets these criteria. Our computerized control system allows one control room operator to monitor and control virtually every function in the plant. We operate with only two engineers on each shift, and two maintenance men on days. This is the kind of streamlined operation the economics of cogeneration demand.

Economy also demands tight scheduling of the overall project. Ground breaking for the Chapleau Project occured September 1985, with foundations poured and erection of the building continuing during the winter of 1986; the boiler and turbine generator arriving during spring and early summer. Commissioning of the partially completed plant began one year to the day after sod turning, and first power was generated October 24, 1986. Construction continued during a period of testing and limited commercial operation until the end of January. We have subsequently been in full load operation since February 1, 1987 with an overall annual plant availability exceeding 90%.

Low energy buy-back rates in Ontario limit the viability of many potential cogeneration projects at present, but I suspect that energy buy-back rates will eventually increase as the true value of small scale parallel generation is realized. But part of the challenge is to demonstrate that private enterprise can effectively design, build and operate thermal

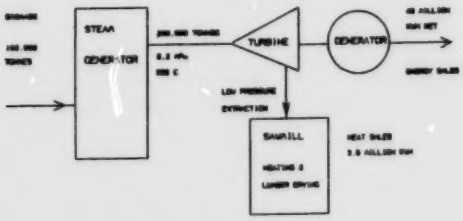
generation facilities capable of reliably delivering a significant amount of energy to the grid.

THE PROCESS

By the time construction started, the Chapleau Co-Generation Project had developed into 7 megawatt wood fired cogeneration plant, burning about 100,000 tonnes per year of sawmill waste. Basic plant parameters, identified in terms of annual quantities are shown in Figure Three. Wood waste from the adjoining sawmill, Chapleau Forest Products Limited, is delivered by belt conveyer. Specially built up tandem dump trucks deliver waste from the other two area mills, both within a 3 kilometer radius of the plant. Fuel processing consists of screening, and pulverizing all material over a four inch cube in a hammer mill.

FIGURE THREE

CHAPLEAU CO-GENERATION



BASIC PROCESS DIAGRAM

The fuel is fired green or wet, drying occurs within the boiler grate. Our combustion technology is based on the Detroit Stoker "Hydrograte". The grate is a water cooled, sloping, vibrating grate, which automatically discharges the ash into a wet ash sluice at the front of the boiler. Adjustment of the grate "jog cycle" permits the operator to respond to changes in fuel consistency and moisture content in a simple and effective way. (Refer to Figure Four "Steam Generator")

FIG. 4

Nine point four kilograms/second steam mass flow, is generated at a pressure of 6.2 megapascals. The steam is superheated to 385 degrees Celsius and delivered to the turbine. Spent, low pressure steam is extracted part way through the cycle to provide steam at 100 kilopascals for drying. The balance of the steam is condensed and returned to the boiler.

The turbine, running at 5,021 rpm, drives the 7,165 kilowatt generator at 1800 rpm through a reducing gear. Electriciy is generated at 14 kilovolts and stepped up to 25 kilovolts by our transformer for export on Ontario Hydro lines. Chapleau Co-Generation is capable of supplying all local energy needs.

Technically, the biggest problem in an energy-from-waste plant is material handling, with combustion a close second. Sawmill waste, with a heating value of 4,000 BTU/lb may be better than Municipal Solid Waste (commonly called garbage), which averages 3,000 BTU/lb, but it is still a low grate fuel. We must burn over four and one half pounds of wood waste to obtain thermal energy we could derive from a single pound of fuel oil. Our fuel averages 50% moisture content, that is, it's half water! As our operators are beginning to learn, burning water is a real art.

Green wood waste is not only relatively low in heating value, which requires us to burn large massses fo fuel (we burn 13.5 tonnes an hour, 324 tonnes per day). It is also a low density material, ranging from 0.23 to 0.29 kilograms per cubic meter. That means that the volumes to be tranported and processed are very considerable. The Chapleau Co-Generation plant burns about 1,120 cubic meters of wood waste every day, enough to bury your house and an ordinary city lot under seven meters of sawdust.

Sawmill waste isn't very well behaved either. It tends to stick, jam, plug, hang up and bridge at every available opportunity. Designing, building and operating machinery which will reliably handle these volumes of material was and is one of our greatest challenges.

THE ENVIRONMENT

The environmental impact of plant operation falls into two main categories regulated by our two environmental Certificates of Approval: air and water.

Since our fuel contains essentially no sulfur, sulfur dioxide emissions are not a matter of concern. Nitrous oxide and carbon monoxide emissions are chiefly related to combustion temperatures and air flows. A study of the combustor design indicated that NOX and CO emissions would not be not be significant in the case. Total particulate emission was the sole remaining matter of concern. Present provincial standards for wood combustion specify maximum emissions of 100 micrograms per cubic

meter (at ground level) at the point of maximum impingement. This requirement was met by a combination of a mechanical multi-cyclone dust separator followed by a Joy type "D" wet scrubber in the base of the stack plus the necessary stack height and flue gas velocity to produce the required dispersion.

Emissions testing results showed in the worst case emissions of 27 micrograms/cubic meter, well below the required standard.

Water pollution was never a matter of concern in this project, since one of the innovative features of our plant design is "zero-discharge" of waste water. All waste water produced from plant processes (floor drains, water treatment wastes, blowdown, etc.) is evaporated in the wet scrubber. Domestic sanitary waste water is sent to an ordinary septic tank. Apart from the environmental advantages, zero-discharge also means lower cost - no waste water treatment is required!

As in the case of air, concerns over environmental impact on water were reduced to a single issue: thermal discharge to the Chapleau River via cooling water effluent. This was a particularly sensitive matter for two reasons: the intake for the town drinking water supply is located 1/2 kilometer downstream of our plant; and an important pickerel spawning bed is located one kilometer downstream. This situation led to the imposition of a number of seasonal temperature limitations. Operating experience to date has demonstrated that our spray pond is effective in maintaining cooling water effluent temperature within the required limits.

THE REWARDS

Pioneering is always tough, and we, that is Foster Wheeler limited, and its operating subsidiary, Chapleau Co-Generation Limited, are in a sense, pioneers. Our success in getting the Chapleau Co-Generation project into production has involved enough frustration and "revisions" to ensure a proper degree of humility. But I think we can say that we do have an operating cogeneration plant that demonstrates the workability of the concept, and in a small way may well be the pioneer and prototype of a significant generation option for the 1990's.

And that is the reward of success: a state of the art facility capable of disposing of 100,000 tonnes per year of sawmill waste, thus converting an environmental problem into a renewable souce of clean useful energy, while at the same time strengthening the economy of Northern Ontario.

TECHNOLOGY DEVELOPMENT STRATEGIES OF THE ENERGY DIVERSITY DIVISION

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The shift in emphasis by the federal government from direct intervention in market activities to a more facilitative role requires new approaches to planning and information management by those involved with technology development and commercialization. The Energy Diversity Division's Planning, Coordination and Liaison group has developed an integrated, technology-based planning process for the assessment and priorization of bioenergy technology opportunities. This process is now being linked to a new comprehensive information system containing data related to bioenergy projects, market participants and pertinent literature.

INTRODUCTION

The S&T Situation

A serious struggle is taking place in Canada over spending for science and technology. The struggle, however, is not directed towards whether there are in existence significant areas of concern. Most people would agree, for example, that the following require attention:*

- Canada's net imports of high technology goods continue to grow; this trend needs to be reversed.
- The proportion of GDP spent on R&D has stagnated. Increased support for R&D is essential to enhance Canada's industrial competitiveness in the 21st Century.
- R&D spending is dominated by the federal government and a relatively small number of corporations. More broadly-based industrial commitments to technology development are needed.

Several policy initiatives to address these problems appear to be in place, including the following:

- The rationale for federal government support of science and technology (S&T) is clearly laid out in the S&T Decision Framework.** Such support is warranted when its purpose is:
  - The enhancement of industrial competitiveness; and/or,
  - The fulfilment of government missions; and/or,
  - The advancement of knowledge.
- The integration of the Ministry of State for Science and Technology within Industry, Science and Technology Canada is taking place.
- The key role of S&T in ensuring Canada's global competitiveness in the next century has been re-confirmed.
- The role for government as a facilitator of market behaviour rather than a direct intervenor has been established.***

Despite these policy initiatives, little appears to be happening to reverse the trends noted above. On the contrary, R&D budgets continue to be constrained, and it is proving difficult to increase the level of collaborative efforts with industry, universities and other stakeholders.

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* Dr. Larkin Kerwin, President, National Research Council, "Rating Canada's Innovation Quotient" The Globe & Mail, March 3, 1989. p. A7.

** A Decision Framework for Science and Technology, Ministry of State for Science and Technology, March, 1987.

*** See, for example, the speech by Robert R. de Cotret, Minister of Regional Industrial Expansion and Minister of State for Science and Technology to the Canada Awards for Business Excellence Presentation Ceremony, Ottawa, September 14, 1988.

One Source of the Problem

Why, despite everyone's good intentions, is more progress not being made? A principle factor may be that, quite simply, people in the federal government are being asked to do business in an entirely new way, without a clear sense of i) what that business is, and ii) just as importantly, how they should be conducting that business. Up to the recent past, in an era of government as intervenor, programs were created to address problems and most federal employees were "doers". With most attention on program implementation, it was appropriate that, in the area of S&T, the bulk of time was spent in conducting or directing R&D projects.

For those involved in the "business" of federal government support of S&T, new mandates are starting to emerge which speak more in terms of the facilitation of technology development than R&D program management. The emphasis is shifting to a role centred on helping market participants identify and take advantage of short and long term technology opportunities.

These new statements of mandate highlight the limitations to the conventional program management orientation:

- Programs tend to be established for a single purpose, which is rarely market-driven;
- Programs tend to be difficult to adapt to changing circumstances in the national and international marketplace; and,
- Programs tend to focus on internal administrative activities and operate in a reactive mode.

A New Focus On Planning

In order to facilitate market behaviour, as required by the new mandates, increasingly it is becoming important that managers of government S&T resources first do their homework to identify, on an ongoing basis, areas of opportunities and interests shared with stakeholders. Doing this homework is an essential component of planning - the process of figuring out what should be done. Put simply, the facilitative role requires that planning - along with implementation - be established as a crucial function performed by government.

Experience of federal government agencies with facilitative S&T mandates is very limited, and literature in the field is practically non-existent. Nevertheless, several premises have been identified on which successful planning activities can be developed.

These premises, and the balance of points discussed in this paper, were identified through the development and introduction of a technology-based planning process by one group (Planning, Liaison and Coordination; within the Energy Diversity Division, Technology Branch, Energy, Mines and Resources Canada (EMR)) and through a review of private sector technology development management practices.

REQUIREMENTS FOR SUCCESSFUL PLANNING FOR ENERGY TECHNOLOGY DEVELOPMENT

The Basic Premises

The four basic premises of successful planning for energy technology development can be considered as:

- Areas of mutual interest among stakeholders include both their general goals (eg., the long-term advancement of a technology area) as well as the translation of these goals into specific terms (eg. applied research on a particular process or product);
- R&D projects cannot be justified solely on their technical merits. Market prospects, economic attractiveness and environmental factors are all relevant and essential to the assessment of S&T opportunities. The appropriate perspective is one of technology development, not simply R&D. Private firms with successful product development programs recognize this and they ensure that meaningful interactions between marketing and research groups take place at all stages of development of a new product;
- A broad array of specific technology opportunities is competing for the scarce S&T resources which are available. These opportunities are characterized by, among other things, differing levels of S&T complexity, differing scales and timing of market impacts and differences as to the nature and size of technology development and commercialization risks; and
- Stakeholders can come from many different types of organizations, including large and small industrial firms, universities, associations, provincial governments, various branches within different federal government departments, international organizations and other groups. Each stakeholder has its own mandate and objectives, structure and systems, and organizational culture, all of which must be understood in the process of developing a plan for joint activities.

Four Dimensions of Integrated Planning

These four premises require that a planning process which assesses opportunities and gains support for joint action be integrative in four ways:

1) "Top down" corporate directions, interests and decision criteria must be integrated with "bottom up" technology-specific knowledge, understanding and access to information;

2) Considerations of technical status and prospects must be integrated with considerations of economic attractiveness, market prospects and environmental implications;

3) The full array of technology opportunities in each broad field of S&T must be assessed - and priorized - in a systematic, objective fashion; and,

4) The planning process must integrate the interests and gain commitment among the diverse set of stakeholders in order to get support for collaborative actions. This can be expected to be successful when the homework part of planning - the assessment of individual technology opportunities - is jointly undertaken and a consensus reached as to its conclusions. In order to bring about the meshing of the interests, views and resources among the diverse group of stakeholders, a planning process "champion" is required. Such a champion: i) must gain acceptance of a workable planning process among stakeholders; and ii) direct the involvement of stakeholders in the two main planning tasks: assessment of opportunities and identification of appropriate actions.

Steps in an Integrated Technology-Based Planning Process

In common with any planning process, an integrated, technology-based planning process consists of four major steps:

Step 1: Establishment of corporate direction:

The objectives, interests and mandate of the planning champion need to be made explicit. Furthermore, these must be combined with planning parameters (such as future economic conditions) to establish "top down" direction which will be employed in the assessment of technology prospects. This corporate direction provides the basis for identifying areas of common ground with other stakeholders and securing their involvement.

Step 2: Assessment of technology opportunities:

Through the analysis of available information, individual technology opportunities can be judged on key decision criteria by a working group familiar with the details of these opportunities. The working group should include representatives of all stakeholders and market and financial, as well as technical, expertise. For each specific opportunity which warrants support, barriers to its development and commercialization can be identified and targeted collaborative action can be recommended.

Step 3: Preparation of the priorized plan:

Stakeholder managements direct resources to those technology opportunities which best meet the priorities for joint support. Since credible detailed assessments have been made by those most familiar with the technology prospects in a framework established by management, resource allocation decisions can be made with confidence on an informed basis.

Step 4: Preparation of the implementation plan:

Roles and responsibilities of stakeholders for all approved support measures are established. Project targets and review procedures are also established to ensure appropriate direction and control over implementation activities.

It should be noted that the usefulness of the assessments of technology opportunities will be in direct proportion to their level of detail. Where stakeholders generate a consensus as to the prospects of specific processes at the detailed level, it becomes a straightforward process to identify appropriate support measures. The generation of consensus among stakeholders is greatly facilitated by the fact that a common base of evidence is assembled, shared and updated on an ongoing basis. Also, it is important that a consistent set of decision criteria be used throughout the assessments.

IMPLEMENTING AN INTEGRATED, TECHNOLOGY-BASED PLANNING PROCESS

Practical Considerations

While it is relatively easy to describe the steps required to conduct integrated technology-based planning, it is more difficult to make generalizations about how these steps should be carried out. Several directions, however, are clear. To start with, the lead role in directing and coordinating the planning activities must be taken by a planning-process champion, an individual or group with a vital stake in the outcome. Such a champion could be, for example, a technology development branch within a Federal government department. Other candidates for the lead planning role might be strong, representative industry associations or non-profit organizations with precise S&T missions.

The carrying-out of the assessments of technology opportunities requires that a working group be established among stakeholders. Initially, assembling the full set of available information may require tightly directed consulting assistance. The working group, however, must be involved in and share a sense of "ownership" with the analysis of information and assessment of opportunities. Throughout the process, the champion must act to educate the members of the working group, as well as senior manager representatives from the stakeholders, as to the purpose, nature and benefits of the planning process. Because individual participants in the planning process continue to be influenced by their organizational cultures, ongoing formal and informal communication activities are necessary to share concerns and suggestions for improving the usefulness of the planning process.

Integrated technology-based planning is inherently complex and time-consuming. However, without the establishment of a consensus view as to general goals, specific technology opportunities and appropriate technology development projects, stakeholders can have little hope of achieving ongoing collaboration nor reaching mutually beneficial goals.

By taking the initiative to place a new focus and emphasis on planning, the federal government can develop a sounder rationale for the commitment of resources in support of S&T in Canada. This rationale - based on the identification of specific short and long term technology opportunities - provides the common ground for establishing effective partnerships with industry and other stakeholders.

PLANNING FOR BIOENERGY TECHNOLOGIES

Experience-to-date

As noted earlier in this paper, a technology-based planning process has been developed and prepared for use within the Diversity Division of EMR's Technology Branch. This process was established to deal with the challenges and opportunities associated with bioenergy technologies.

Bioenergy technologies represent a substantial part of the mandate of the Energy Diversity Division. Within the broad arena of bioenergy are found several well-established, significant energy contributors, such as hog fuel and recovery boilers. As well, a very broad range of technologies are being considered for possible future roles in the marketplace. Some are simple and straightforward, others extremely complex and even estoric. Some draw heavily on traditional forest products' scientific knowledge, while others represent emerging areas of biotechnology. Possible market opportunities include applications as diverse as residential space heating, large industrial cogeneration systems and automotive transportation fuels.

By 1988, it became clear that the increasing complexity and diversity of bioenergy technology opportunities was straining the capabilities of existing planning practices. Thus, the EMR bioenergy team was receptive when approached with the idea of a process which would:

i) Assemble and make accessible for planning purposes the vast amount of information that has been produced on bioenergy in Canada;

ii) Conduct a comprehensive, systematic assessment of all opportunities for bioenergy technology applications in the marketplace of today and the future. Such an assessment would include technical, financial, market and environmental analyses of each opportunity;

iii) Identify which of these technology opportunities was worthy of Federal Government support; and,

iv) Recommend specific support measures for those opportunities deemed to be worthy of support.

These planning activities were carried out in several stages between April 1988 and March 1989. It should be noted that these stages correspond to the first two general planning process steps outlined earlier in this paper, the establishment of corporate direction and the assessment of technology opportunities. As discussed at the end of the paper, the second two steps (preparation of the priorized plan and the implementation plan) have not yet been carried out.

Stage 1: Establishment of Definitions

The central activity of a technology-based planning process is the assessment of specific technology opportunities with a view to determining whether they are worthy of support. Operational definitions were established, therefore, for the three components of this assessment process: 1) Technology opportunity;
ii) Criteria for assessment; and
iii) Opportunities worthy of support.

Technology Opportunity: The "PAT"

For consideration as having an opportunity, a technology must be considered in the context of its prospective market activity. Thus, a technology opportunity was first defined as a Prospective Application of Technology or "PAT". For bioenergy technologies, a PAT is considered to consist of the linkage of four components which, in combination, represent the major determinants of possible success for a new technology:

a) Inputs (eg., various feedstocks)

b) The Conversion Process (eg., fast pyrolysis)

c) Output Products (eg., heavy oil substitute)

d) Market Application Segments (eg., industrial process)

Within bioenergy, PAT's can be simple, such as fuelwood burned in wood stoves for residential space heating, or exceedingly complex, such as the fractionation of dry particulate solid fuel from various feedstocks with further processing of the fractions to produce transportation fuels and chemical products.

Criteria and Decision Rules

In order to determine whether a technology opportunity is worthy of EMR support (ie., whether the possible market impacts of a PAT are desirable), assessment criteria and decision rules were established. These were based on four main sets of considerations flowing from top-down EMR corporate direction.

The four main criteria (ie., the measuring sticks on which assessments of technology opportunities were made) were as follows:

- Technical feasibility is achievable;
- Financial attractiveness will meet investor criteria at the crude oil price forecast ceiling;
- Significant market potential and energy impact will be available and can be exploited by suppliers; and,
- Environmental implications will be acceptable.

The specific decision rules (ie., requirements for acceptance) which were established for these criteria were as follows:

- Reasonable likelihood of market readiness by the year 2010.
- Attractive to decision makers if crude oil is no higher than U.S. $32/bbl (1988 $) in 2010.
- A minimum of 2 PJ in annual potential displacement of conventional energy sources and products. Resource availability, supplier capability and institutional infrastructure expected to be in place.
- Negative environmental impacts to be less than those of the displaced energy source.

Technology Opportunities Worthy of Support: PAT Winners and Contenders

Based on an assessment of available information related to each criterion, PAT's can be assessed to determine whether they should be designated as a "winner", "contender" or "outsider". These were defined as follows:

"Winner" Based on a high level of confidence in the available information, EMR management fully supports a PAT winner for its appropriate market applications. Two types of winners can be designated. A "Winner In Place" is a technology application which has currently penetrated a portion or all of its market potential. Examples: Hog fuel boilers at pulp and paper plants; residential air tight wood stoves. A "Winner Within Planning Frame" is a technology application which is not currently in place in Canada (although technically proven elsewhere) but which meets the planning frame criteria of being financially attractive at the higher energy prices predicted or occurring within the planning horizon, ie. by the year 2010. Examples: residential space heating from wood pellets; air gasification for industrial process heat requirements fuelled by wet hog fuel. EMR can promote the adoption of both types of winners in the marketplace.

"Contender" A technology opportunity which EMR management views as promising and likely to meet all four decision rules is called a contender. However, due to lack of certain types of information (eg. inconclusive data re emissions, operating efficiencies in scaled-up facilities or financial attractiveness), it is premature to give the opportunity the green light to promote in the market. Examples: Heavy oil substitute from fast pyrolysis for large industrial process boilers and substitute natural gas from pyrolytic gasification for institutional space heating boilers. In the course of the assessment of a contender PAT, the specific gaps in available evidence are identified and provide a precise targeting of objectives for recommended support measures. As missing information is then obtained through these measures (such as R&D projects, market studies, financial analyses and other sources), the expectations for the PAT may be confirmed. In this case, the PAT will move from the contender to the winner category. On the other hand, if the additional evidence does not allow support of the assessment criteria, the PAT may have to be re-categorized as an outsider.

"Outsider" A technology opportunity which falls outside of current criteria and decision rules for EMR support is called an outsider. Example: wood-based DBF logs for residential space heating are not considered worthy of support since they are judged to be financially unattractive. It should be noted that, over time, either decision criteria or judgements concerning a technology's prospects may change. Thus, periodic reviews are required to determine whether any outsider opportunities have become contenders or winners, or vice versa.

Stage 2: Organization of Information

With an assessment procedure established, the next stage of activity involved the identification of what types of information were required and how this information could be assembled and analyzed in order to be most useful. Four types of information were seen as required, as determined by the four decision criteria:

i) Technology Status and Prospects
For each PAT, an understanding of the current technical status of the conversion processes(es) and the prospective development prospects, issues and risks is required.

ii) Financial Attractiveness

The analysis of financial attractiveness of a PAT is based on an analysis of relevant costs, savings and revenues associated with the PAT in relation to its competition (both as conventional systems or other bioenergy systems).

iii) Market Prospects

The principle determinant of competitive advantage for bioenergy PAT's (and hence the extent of their market opportunity) is the level of their financial attractiveness. In order to translate a particular level of financial attractiveness into a forecast of potential market impact, several additional types of information are needed, including:

a) Patterns of feedstock availability and cost; b) Capabilities of equipment suppliers and installers; c) Number and location of prospective end users within the application segment; d) Current end user attitudes and purchase practices; e) Role of existing codes and need for new standards and certification procedures; f) Likely competitive response to the introduction of bioenergy systems.

iv) Environmental Implications

The nature and extent of positive and negative environmental implications of the prospective technology opportunity is required to determine whether the PAT would be be acceptable. Environmental impacts could be registered at the feedstock procurement level (such as forest management practices), during feedstock processing (such as drying or chipping), in conjunction with further processing (such as anaerobic digestion or densification) or in the final conversion process and disposal of wastes (such as MSW incineration or residential woodstoves).

The assembling of the types of information outlined above was found to be a major undertaking. In many cases, needed information was either found to be in several locations, not complete, contradictory, or not in a format to be of use. In other cases, information was simply not available. The steps taken to organize and increase the usefulness of available information were as follows:

i) A new bioenergy technology classification system was established.*

ii) A computerized information system (BITTS) was implemented to obtain, validate and make accessible information related to bioenergy R&D studies, installations and other projects. In addition, directories of suppliers and installations are being prepared.**

iii) Extensive technology status and prospects reference documents were prepared by consultants for eight major bioenergy technology areas.

iv) A financial analysis software model was used to assess the financial attractiveness of PAT's. This model (called "RETA") has been developed as part of EMR's leadership role with the International Energy Agency's Renewable Energy Working Party.***

v) Detailed lists were prepared of all conceivable PAT components: bioenergy feedstocks, conversion processes, outputs and market applications. From these lists, which ran for over 50 pages:

a) Components which were judged to have no prospect at all of being part of a winner or contender were deleted; remaining components were combined into sub-groups.

b) Four categories of energy market applications were established:

. Residential Space Heat
. Non-Residential Space Heat
. Industrial Process Heat
. Transportation Fuels.

c) Four categories of conversion processes were established:

. Feedstock Processing (eg., comminution, drying)
. Primary Conversion (eg., densification, pyrolysis)
. Secondary Conversion (eg., fermentation, upgrading)
. Combustion (eg., boilers, combustors)

d) A "PAT MAP" was prepared to show the relationships among feedstocks, processes, outputs and market applications. (see Figure 1); and,

e) Approximately 60 PAT's were identified as being worthy of consideration. An example of one of these PAT's is shown in Figure 2.

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* Bioenergy Technology Classification System prepared by Ensyn Engineering Associates Inc., included in "Volume 8: Supporting Documentation" of the PAT planning process documentation reports (see Appendix 2).

** Bioenergy Information and Technology Transfer System, Marbek Resource Consultants, Seventh Canadian Bioenergy R&D Seminar, Ottawa, April, 1989.

*** A Standard Methodology for Estimating the Cost, Performance and Economic Viability of Renewable Energy Technology Applications, J.C. Barclay et al, Seventh Canadian Bioenergy R&D Seminar, Ottawa, April, 1989.

Stage 3: Assessment of PAT's

The PAT's were assessed on the four decision criteria discussed earlier in this paper. An illustration of the results of one such assessment is presented in Table 1. The final designations of 61 PAT winners and contenders resulting from the assessments are listed in Appendix 1. A tally of these designations is shown in Table 2.

For each winner and contender, appropriate support measures have been recommended. In general, winners are well established technologies and require little support. For many contenders, it has been found that an immediate need exists to conduct financial analyses under current planning parameters and, based on the results of these analyses, develop assessments of market prospects.

Stage 4: Documentation

Eight volumes of documentation have been prepared. (See Appendix 2 for the complete list of volume titles.) These include:

- A summary for management containing highlights of the assessment procedure and results;
- The individual PAT assessments, organized by the four market application areas; each assessment includes a summary, two pages of description, two pages of assessment findings and two pages for determination of recommendations;
- The technical status and prospects reference documents; and,
- Supporting information, including copies of 24 pertinent articles found in the literature.

The total of close to 1,000 pages of documentation would first appear to be a bureaucrat's view of heaven. However, the large amount of documentation is required because bioenergy consists of such a broad set of technologies with many and varied opportunities. The documentation has been organized in such a way as to be useful on a day-to-day basis by all prospective users - project officers and managers within the federal service and by all other interested agencies. It represents the accumulation and synthesis of what is known - and is not known - about each of the technology opportunities deemed to be worthy of support. This material has become part of a larger information system (including the BITTS database system) designed to provide a dynamic focal point of knowledge and understanding of prospects for bioenergy technology development and commercialization in Canada.

THE ROAD AHEAD

To date, the planning group of the Diversity Division has spearheaded and funded the development of the first round of technology-based planning for bioenergy. The challenge at this point is to translate the results of this initial organization, assessment and documentation activity into an ongoing planning process accepted and used by EMR in its dealings with stakeholders.

The next task is to complete the first planning cycle within the Diversity Division. Reviews of the documents with bioenergy project officers are planned for initiation in May and many refinements and additions are expected. The goal of this review activity is to transfer the sense of understanding and "ownership" of the individual technology opportunity assessments to the EMR technology development officers.

Traditionally, the focus of this group has been primarily technical in nature. Since they are now being asked to also be knowledgeable about financial, market and environmental dimensions of technology development, it is expected that the full transfer of "ownership" of planning outputs will take some time.

It will also be necessary to conduct a detailed priorization process among specific opportunities. Choices will have to be made by management among the recommended support measures.

Finally, the planning process must reach out and involve other stakeholders. Whether from industry, academia or other government departments, these stakeholders must be invited to i) understand the explicit set of considerations which are leading to EMR's targeted support activities; and ii) contribute their knowledge and views. The goal here is ensure that the multi-dimensional information base is not managed solely for EMR's interests; rather, it represents a most valuable resource which can more effectively guide all Canadian support of bioenergy technology development and commercialization.

Table 1

Illustration of a Pat Assessment

PAT: Fuel Chips For Residential Space Heating

1) TECHNOLOGY STATUS/PROSPECTS:

- Equipment developments have been underway to reduce capital cost and increase reliability and convenience of small automated chip systems. Installed costs, however, remain high.

2) FINANCIAL ATTRACTIVENESS

- The first set of financial analyses indicate that, at current costs for equipment and for chips, the cost of useful heat from retrofit chip systems is higher than from light fuel oil, even at high oil prices.

3) MARKET PROSPECTS

- If viable, wood chip systems would compete directly with light fuel oil and wood pellet systems and indirectly with fuelwood systems. With no financial advantage, however, market potential is non-existent.

4) ENVIRONMENTAL IMPLICATIONS

- Chip systems produce less SO_2 but more particulate emissions than oil burning systems. Biodegradation of chips in storage may produce spores, a potential health hazard.

CONCLUSION

In order for residential chip burning to remain a contender, opportunities for significant reductions in capital and/or fuel chip costs must be identified.

Table 2

RESULTS OF ASSESSMENT OF PAT CLUSTERS

MARKET APPLICATION	WINNERS IN PLACE	WINNERS PLANNING FRAME	CONTENDERS	TOTAL
RESIDENTIAL SPACE HEATING	1	2	4	7
NON-RESIDENTIAL SPACE HEATING	-	1	4	5
INDUSTRIAL PROCESS	6	7	9	22
TRANSPORTATION FUELS	-	1	4	5
FEEDSTOCK PROCESSING	8	2	12	22
TOTAL	15	13	33	61

NOTE: PRELIMINARY TALLY; FOR DISCUSSION PURPOSES
Details are included in Appendix 1.

Figure 1

PAT MAP SHOWING RELATIONSHIPS AMONG FEEDSTOCKS, PROCESS INPUTS, CONVERSION PROCESSES, PROCESS OUTPUTS AND MARKET APPLICATIONS

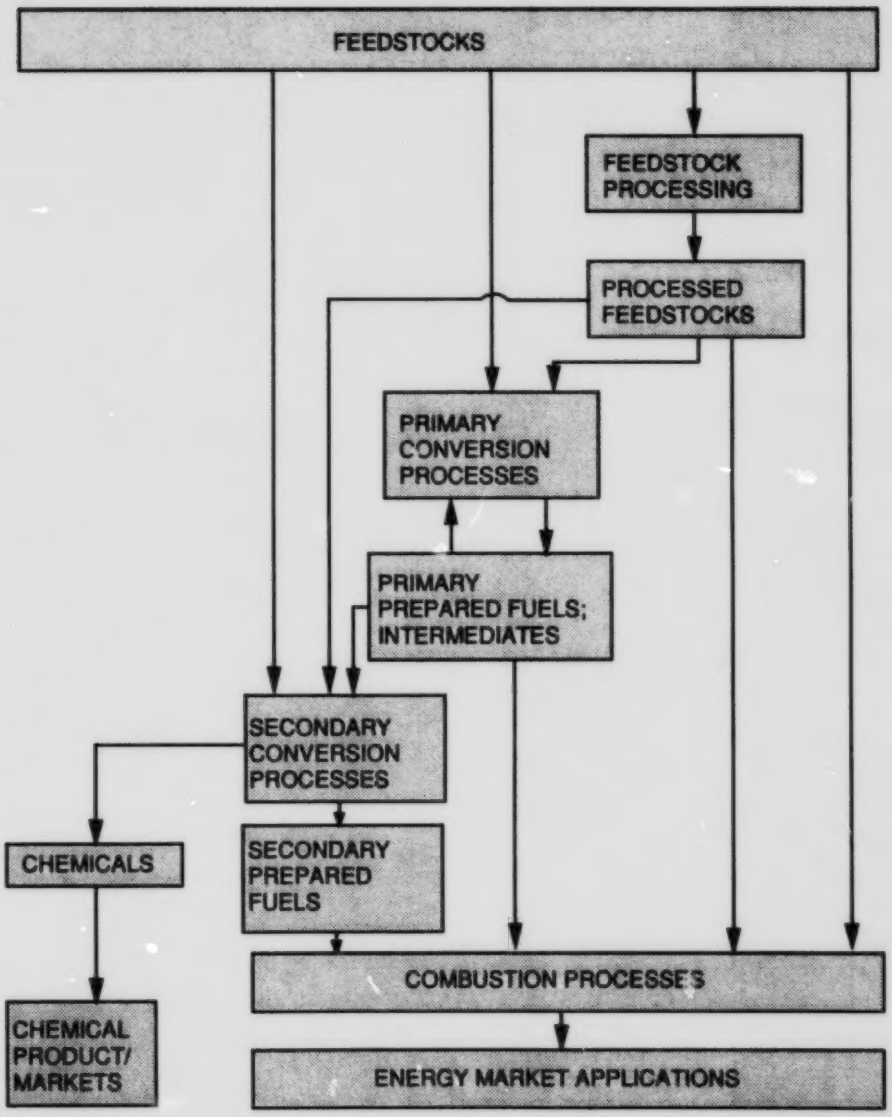
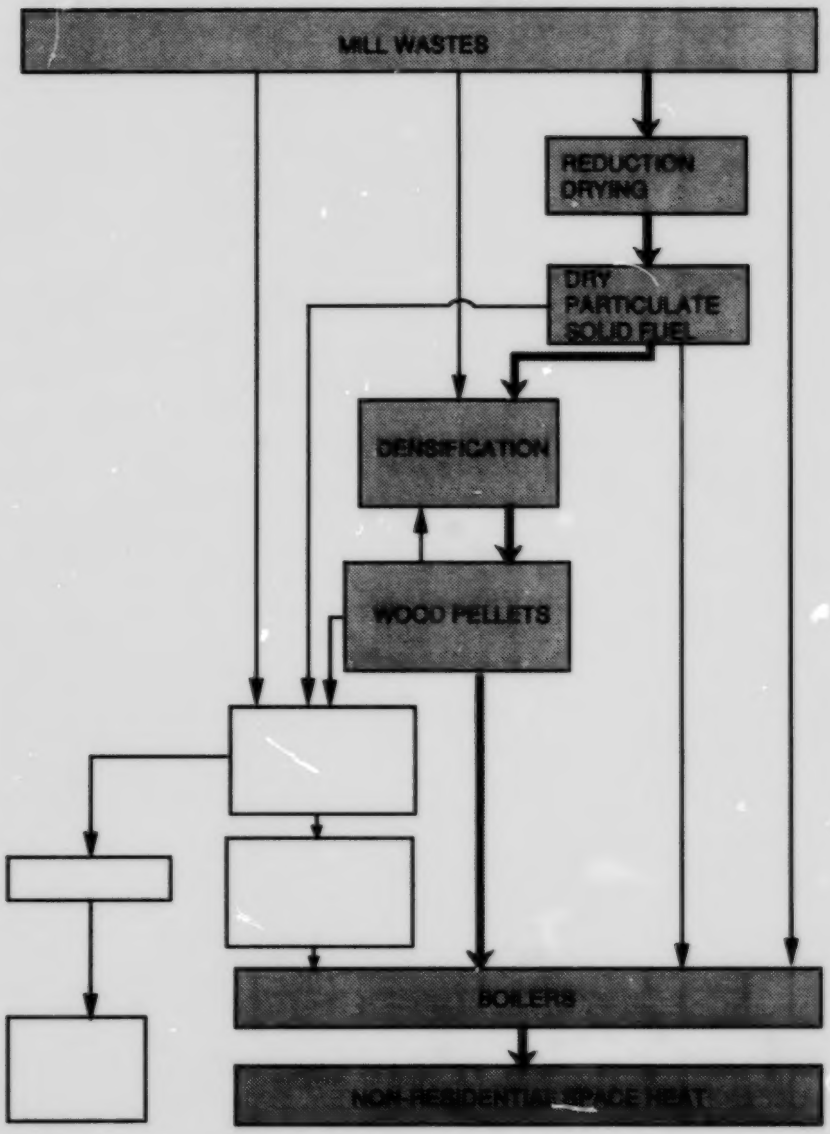


Figure 2

EXAMPLE OF A PAT: WOOD PELLETS FOR NON-RESIDENTIAL BUILDINGS



APPENDIX 1

Final Designations of PAT Winners and Contenders*

I. **Residential Space Heat**

A. **Winners In Place:**

RES-WIP-1: Residuals/Stovewood/Stoves, Boilers, Furnaces/Space Heat

B. **Winners Within Planning Frame**

RES-WPF-1: Plantations/Stovewood/Stoves, Furnaces, Boilers/Space Heat

RES-WP-2: Dry PSF/DBF/Stoves, Furnaces, Boilers/Space Heat

C. **Contenders**

RES-CON-1: Wet PSF, Dry PSF/Furnaces, Boilers/SpacesHeat

RES-CON-2: Dry PSF, etc./Fast Pyrolysis, Solvolytic Liquefaction/Light Oil Substitute/Furnace, Boiler/Space Heat

RES-CON-3: Wet Hog, etc./Digesters, Landfill Gas, Pyrolytic Gasification, Oxygen Gasification/Substitute Natural Gas/Furnaces, Boilers/Space Heat

RES-CON-4: Residuals, Plantations/Chips/ Furnaces, Boilers/Space Heat

---

* Abbreviated terms are defined at the end of the listing.

APPENDIX 1

II. **Non-Residential Space Heat**

A. **Winners In Place**

- None -

B. **Winners Within Planning Frame**

NRS-WPP-1: Chips, DBF, Wet Hog/Furnaces, Boilers/Space Heat

C. **Contenders**

NRS-CON-1: Bio-chunks/Furnaces, Boilers/Space Heat

NRS-CON-2: Wet hog, etc./Thermal Oil Heaters, Furnaces, Boilers/Space Heat

NRS-CON-3: Dry PSF, etc./Fast Pyrolysis, Solvolytic Liquefaction/Light Oil Substitute/Furnaces, Boilers/Space Heat

NRS-CON-4: Wet Hog, etc./Digesters, Landfill Gas, Pyrolytic Gasification, Oxygen Gasification/Substitute Natural Gas/Furnaces, Boilers/Space Heat

III. Industrial Process

Group 1: Very Large Boilers

A. Winners In Place

IND-WIP-1: Hog Fuel/Boilers/Process Steam

IND-WIP-2: WDF, RDF/Boilers/Process Steam

IND-WIP-3: Black Liquor/Recovery Boilers/Process Steam

B. Winners Within Planning Frame

IND-WPF-1: Chips, DBF, Wet Hog/Furnaces, Boilers/Space Heat

IND-WPF-2: DBF/Boilers/Process Steam

IND-WPF-3: WTC/Boilers/Process Steam

C. Contenders

IND-CON-1: Bio-chunks/Boilers/Process Steam

IND-CON-2: Wet hog, etc./Digesters, Landfill Gas, Pyrolytic Gasification, Oxygen Gasification, Air Gasification (certain feedstocks)/ Substitute Natural Gas/Boilers/Process Steam

IND-CON-3: Dry PSF, etc./Fast Pyrolysis, Solvolytic Liquefaction/Heavy Oil Substitute/Boilers/Process Steam

Group 2: Very Large Combustors

A. Winners In Place

- None -

B. Winners Within Planning Frame

IND-WPF-4: DBF/Combustors/Process Heat

IND-WPD-5: Wet Hog, etc./Digesters, Landfill Gas, Pyrolytic Gasification, Oxygen Gasification, Air Gasification/Substitute Natural Gas/Combustors/Process Heat

C. Contenders

IND-CON-4: Dry PSF, etc./Fast Pyrolysis, Solvolytic Liquefaction/Heavy Oil Substitute/Combustors/Process Heat

IND-CON-5: Wet Hog, etc./Combustors/Process Heat

III. Industrial Process (Cont'd)

Group 3: Small / Medium Industrial

A. Winners In Place:

IND-WIP-4: Chips/Boilers/Process Steam, Heat

IND-WIP-5: Hog, PSF/Boilers, Combustors, Thermal Oil Heaters/Process Steam, Heat

IND-WIP-6: Digesters/Boilers/Process Steam

B. Winners Within Planning Frame

IND-WPF-6: Chips, DBF/Boilers, Thermal Oil Heaters/Process Steam, Heat

IND-WPF-7: Wet Hog, etc/Air Gasification/Substitute Natural Gas/Boilers/Process Steam, Heat

C. Contenders

IND-CON-6: Dry PSF, etc./Fast Pyrolysis, Solvolytic Liquefaction/Heavy Oil Substitute/Boilers/Process Steam

IND-CON-7: Wet Hog, etc./ Digesters, Landfill Gas, Pyrolytic Gasification, Oxygen Gasification, Substitute Natural Gas/Boilers/Process Steam, Heat

IND-CON-8: Small Bio-chunks/Boilers/ Process Steam, Heat

IND-CON-9: Plantation Chips, Yard Debris Hog/Boilers/Process Steam, Heat

IV. Transportation Fuels

A. Winners In Place:

- None -

B. Winners Within Planning Frame

TSP-WPF-1: Cereal Grains/Fermentation/Ethanol

C. Contenders

TSP-CON-1: Wet Hog,etc./Fractionation/Hydrolysis/Fermentation, Lignin Processing/Fuels, Polymers, Plastics, Chemicals

TSP-CON-2: Oil Substitute/Hydrotreating or Cracking/Gasoline or Diesel or Additives

TSP-CON-3: NG Substitute/Methanol Synthesis/Methanol/Mobil Synthesis/Gasoline

TSP-CON-4: Pyrolytic Gas/Polymerization/Gasoline, Petrochemicals

APPENDIX 1

V. Feedstock Processing

A. Winners In Place:

FSK-WIP-1: Forest Residuals/Block, Split/Stovewood

FSK-WIP-2: Forest Residuals/Chipping/Fuel Chips

FSK-WIP-3: Mill Wastes/Reduction, Drying/Dry PSF

FSK-WIP-4: MSW/Reduction, Separation/RDF, WDF

FSK-WIP-5: Liquors, Tall Oil/Concentration/Heavy Oil Substitute

FSK-WIP-6: Starch Crops/Pretreatment/Aqueous Solution

FSK-WIP-7: Oilseeds/Reduction, Dry PSF

FSK-WIP-8: Mill Wastes/Reduction, Drying, Extrusion/DBF

B. Winners Within Planning Frame

FSK-WPF-1: Yard Debris/Reduction, Separation, Reduction/Wet Hog

FSK-WPE-2: Plantations/Harvesting, Block, Split/Stovewood

APPENDIX 1

V. Feedstock Processing (Cont'd)

C. Contenders

FSK-CON-1:	Peat/Drying, Optional Reduction/Bio-chunks, Dry PSF
FSK-CON-2:	Tree Components, Brush, Slash/Reduction, Drying/Dry PSF
FSK-CON-3:	Yard Debris/Separation, Reduction, Drying/Dry PSF
FSK-CON-4:	Forage/Compaction, Reduction, Optional Drying/Wet PSF, Dry PSF
FSK-CON-5:	Agricultural Stalks/ Compaction, Reduction, Drying, Reduction/Dry PSF
FSK-CON-6:	Sludges, Manures/Add Water or Dewater/Aqueous Solution or Wet, Dry Hog, PSF
FSK-CON-7:	Course Wet Industrial Residues/Dewater/Aqueous Solution or wet, Dry Hog, PSF
FSK-CON-8:	Fine Wet Industrial Residues/Dewater, Optional Drying/Wet, Dry PSF
FSK-CON-9:	Fine Dry Industrial Residues/Screen/Dry PSF
FSK-CON-10:	Tree Components/Chunking/Small Bio-Chunks
FSK-CON-11:	Plantations/Harvesting, Chipping/Fuel Chips
FSK-CON-12:	Plantations/Harvesting, Shredding/Wet Hog for Densification

DEFINITIONS OF ABBREVIATED TERMS

PSF: Particulate Solid Fuel

DBF: Densified Biomass Fuel

MSW: Municipal Solid Wates

RDF: Refuse Derived Fuel

WDF: Waste Derived Fuel

WTC: Whole Tree Chips

APPENDIX 2

List of Titles for PAT Planning Process Documentation

VOLUME 1:	Summary Report Bioenergy Technology Opportunities Assessments and Recommendations
VOLUME 2:	Bioenergy Technology Opportunities Residential Space Heating PAT Assessment and Recommendations
VOLUME 3:	Bioenergy Technology Opportunities Non-Residential Space Heating PAT Assessment and Recommendations
VOLUME 4:	Bioenergy Technology Opportunities Industrial Process Heat and Steam PAT Assessment and Recommendations
VOLUME 5:	Bioenergy Technology Opportunities Transportation Fuels PAT Assessment and Recommendations
VOLUME 6:	Bioenergy Technology Opportunities Biofuel Feedstock Processing PAT Assessment and Recommendations
VOLUME 7:	Bioenergy Technology Status and Prospects Reference Documents
VOLUME 8:	PAT Planning Process Supporting Documentation

TRANSPORTATION ENERGY IN 2010 AD
A TECHNOLOGY PROSPECTIVE

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Techtrol Limited
Montreal, Quebec

Four factors will shape our future energy sources: Environmental Impact, Technology, Security of Supply and Economics. Each factor will be addressed separately.

During the next 20 years we foresee our liquid fuel options as being Oil, Methanol, and Ethanol. Oil needs no introduction; Methanol is derived principally from natural gas and Ethanol is an agricultural product. The recent history of government involvement in Canadian energy supply indicates that oil now rivals agriculture as a drain on the public treasury. It is hence appropriate to consider the potential effect of any change in energy source on institutionalized current support programs.

Another possible transportation "fuel" could be electricity. The possibility for electric powered vehicles however, requires a break-through in battery or fuel cell technology. This option will be dealt with in the economics section as a cost comparison with oil.

ENVIRONMENTAL IMPACT

Historically, qualification for a viable hydrocarbon has been based solely on performance. Does the selected chemical perform as a fuel? Is it the least cost alternative? Environmental issues were considered irrelevant and largely dismissed. It is note-worthy that Environment has now reached the agenda.

There are two separate environmental considerations; Local and National Impacts. There is also the practical need to achieve an acceptable balance between affordability and public safety.

Local Issues

These cover toxic emissions from both combustion and evaporation and include lead, aromatics, carbon monoxide, etc. Toxic substances can now be removed or significantly reduced. The use of lead in automotive fuels has been banned by legislation in the United States and is scheduled to be phased out in Canada in 1990. The aromatics, which are carcinogenic, can be reduced by modifying processing conditions. Evaporative emissions can be improved by lowering gasoline vapor pressure through reduced butane content. Carbon monoxide can be dealt with by adding oxygenates to the fuel. California has opted to reduce toxic emission problems within its jurisdiction by introducing alcohol fuels. To date, methanol has been favoured because of its low cost. An encouraging press release by The Honorable Lucien Bouchard, Minister for the Environment, asserted that within 5 years Canada will have the most stringent anti-pollution laws that are practical. Toxicity abatement is now affordable and the public mood will no longer endorse the externalization of pollution cost nor accept the continuation of pollution as a profit centre.

National Issues

The significant National Environmental Issue is the "Greenhouse" Effect. Included below is a mathematical model showing the build-up of carbon in the atmosphere. This model is based upon two generally accepted criteria; a 40% carbon flux rate and a 3 ^{o}C temperature increase as a result of doubling the current atmospheric CO_2.

The graph in Fig. 1 shows the effect of linearity between carbon build-up and temperature rise; that is, a 3 ^{o}C temperature rise will result from each additional 0.320 PPM of CO_2 in the atmosphere. These calculations fit closely with a 1987 European model by Maier-Reimer and Hasselmann. Two energy growth projections have been tested, 4.3% as the high and 2.3% as the low growth scenarios.

Using these assumptions, the significant conclusion is that it will require 55 years to raise Global temperature the first 3°C but only 15 further years to achieve an increase of an additional 3°C . The graph dramatically depicts a problem similar to the apparently inexorable growth in our current budget deficit. The sloping line tangential to the curve on the high growth scenario shows the continued CO_2 build-up even assuming we were to stop further CO_2 growth in 2045. We must however point out that atmospheric forecasting is an imprecise science and either a more serious or less serious scenario could be possible. The calculations nevertheless serve as a significant warning.

Since energy use is a measure of national prosperity and the developed countries are the main offenders, we cannot reasonably cap expansion in the underdeveloped countries. The developed countries will not easily accept lower living standards. They will instead demand action to address the problem so that economic growth can be maintained. It is generally accepted that conservation and energy efficiency alone will not be adequate to do the job.

A new, economic, clean fuel technology using a globally based resource is necessary to deal with the broad devastation which could result from the "Greenhouse" effect.

Affordability aside, no public consensus has developed to date on what should be done to resolve the "Greenhouse" problem or how the cost and responsibility should be shared. Suggestions have been made that we must preserve the tropical jungles and plant more trees. In order to understand the importance of trees a sketch on Tree Growth Kinetics was developed (Fig. 2).

Trees

Vegetation acts as the lung of the universe. Foliage converts solar energy and CO_2 into biomass by a photosynthesis reaction and releases oxygen. Combustion of biomass in any form will recycle the CO_2 into the atmosphere. Obviously augmenting the landbase devoted to tree growth is an integral part of a solution to the "Greenhouse" effect.

TECHNOLOGY

Technologies for oil and methanol production are mature and we would expect little improvement. Biomass utilization, however, is an area where technology can continue to improve the price/performance ratio. Burning and pyrolysis present some opportunity based on improvement in plant yield. The greatest advances have, however, been made in ethanol production from biomass.

Most ethanol produced in the United States for fuel applications uses corn as the feedstock. The process for converting ligno-cellulosics to ethanol very closely parallels that of corn in yield/tonne and in the process steps required. The historical technological limitations are being rapidly overcome.

Bioenergy - Ethanol from Biomass

Three Economic/Technical constraints previously stood in the way of the biological liquefaction of wood.

- Breaking the ligno-cellulosic bonding was economically achieved in 1979 by steam explosion.
- The development of enzymes to cleave the glucose bonds has improved geometrically and that improvement continues to accelerate.
- New plant genetic strains have improved biomass productivity by a factor of five.

Technical progress has, in fact, been so rapid that economic analysis to follow the developments quickly became outdated. A new EM&R model, sponsored by the Bioenergy Development Program will be ready shortly and information from this model will allow decision making to remain current.

As the biomass industry matures, ethanol could move rapidly into competition with oil, even at current prices. The advantage of no "net" addition of CO_2 to the atmosphere and the substantial reduction in other emissions will ensure a strong position for Bioenergy and particularly ethanol in the liquid fuels area.

Methanol

We expect methanol prices to move upwards from 15c/litre to 24c/litre over the intermediate term in concert with an equivalent downward shift by ethanol. Both methanol and ethanol will equivalently improve the local pollution environment. Methanol however, has only marginal effect on CO_2, the main "Greenhouse" emission.

Canadian Research Priorities

The stated priorities of the government have been "Conservation and Sustainable Development". This however, has not been the priority of our energy research as indicated by a 1987 EM&R publication.

Canadian Energy R & D Spending

Nuclear energy has lost public confidence after almost fifty years of promotion (Fig. 3). It is probably not the low cost option at this time but has been particularly favoured with 57% of the total budget. Bioenergy on the other hand, the only "Sustainable" energy source which holds promise of a solution to the "Greenhouse" problem, has had only 2% of the energy research budget. Part of the rigidity in the OERD decision making process appears to lie in the review system. A sector is selected each year for review and is analyzed separately for its internal efficacy. This introduces improvement at the margins without addressing the overall program distribution to reflect technological advances or priority changes which may have taken place in response to current public concerns.

We estimate that the requirement for maintaining Canadian world leadership in biomass conversion is a six year Research and Development Program with a $15 million per year budget. Support at this level would mature a cost competitive Bioenergy Industry, irovide for on-going plant genetics and biotechnology research, tree plantation "scale up", and process demonstration. This is a small commitment by overall EM&R budget standards.

The obvious advantages of a biomass initiative leads to the question: Is Bioenergy plausible on a broad scale? The following chart shows that the land needed for the replacement of world gasoline by ethanol is well within reasonably achievable

limits and that biomass could fulfill the requirement of a "Global" based resource.

Supply Logistics

Portion of Agricultural Land required to allow Ethanol to replace Gasoline.

Basis: 300 litre per tonne, 300 tonnes per hectare

Canada	8.0%
United States	14 %
United Kingdom	30 %
France	19 %
West Germany	69 %
Italy	26 %
Japan	282 %
USSR	5.3%
Australia	0.5%
China	5.3%
Brazil	1.2%
Mexico	2.9%
India	2.1%
Argentina	0.8%

Weighted Average 5.9%

Subsidies

Biomass represents a major opportunity for Farm Diversification. Hybrid trees should be cost compensatory for farmers at $20.00 per tonne, a totally reasonable target. This would obviate the necessity for current farm subsidies which range from 20% to 50% of total farm production cost.

ENERGY SECURITY

Energy Security is a political issue. It is perhaps worthwhile to define our security needs. Stationary power plants can substitute coal or natural gas for oil and hence do not represent a security concern. The security issue, in effect, is solely a potential shortage of transportation fuels. Like defence policy, energy security policy is highly subjective and expenditure decisions do not necessarily have to have rigorous justification. This is probably why oil now rivals agriculture as a beneficiary of public funding.

Within the security umbrella we will look at the two aspects; World Supply and National Availability for each of oil, methanol and ethanol.

Oil

World Supply

The known global light crude reserves represent in the order of 34 years current demand (BP Statistical Review, 1986). These reserves are becoming increasingly localized. A 75 year supply is projected at moderate cost ($25 - $30 /BBL) and very large supplies at a higher cost ($35 - $40 /BBL). Price is the main factor in global supply.

National Supply

Canada's National position is shown in Fig. 4 as submitted by Husky to the Parliament Committee on National Resources. It indicates that five major frontier projects, Terra-Nova, Hibernia, Amauligak, Husky Heavy oil and an In-Situ Plant need to be brought into production to hold Canada above a 50% self sufficiency level in 2000 AD. As indicated, the United States is in much the same depleting supply position but does not have Canada's "Frontier" reserves.

We support the Government's decision to proceed with the Frontier development on a security basis but would have preferred the Husky suggestion of corporate bidding for additional supplies rather than ad hoc negotiations.

Methanol

Methanol feedstock is widely distributed.

Ethanol

Ethanol is a global uniquely sustainable energy source which would obviate the security problem over most of the world.

ECONOMICS

Oil - Made in Canada

The Canadian Oil Industry seeks to be identified as staunchly "Free Market". The fact however, is that the industry refuses to invest in long-term energy exploration without major government support and price safety nets. Approximately $15 billion in public funds has been spent or committed during the past 10 years in PIP grants and Frontier Oil programs. The fact that Saudi Arabia could drop the oil price to $7.50/BBL at any time makes any energy project unbankable without government backstops.

When analyzing Frontier Oils, our economists and the government endorsed an "Unburdened" cost of $25.00/BBL which is on average 35% below the fully accounted cost. The resulting fully accounted Frontier costs are close to twice the reference price of $18.00/BBL at this time. Grants and soft loans have been provided to shift the actual costs down to the current market price. (Unburdened cost excludes the "net back" to Canada from the industrial activity generated by the development). This principle is perhaps a reasonable position within the Canadian context. We inhabit a land which is massively underdeveloped but which still has major unemployment outside the cities. This thesis should be extended to promote other national priorities such as the "Environment" and "Clean Fuels". However, supporting development for which the unburdened cost exceeds "World" oil prices may be questionable.

The cost analysis used to justify the use of special incentives for Frontier Oil introduces a distortion which might be called the "Asphalt factor". The security of supply issue is a

concern involving a shortage of transportation fuels. Since only 50% of the Frontier Oils will end up as transportation fuels, the other half being used in asphalt and other substitutable products, it would be appropriate that the Total government incentive be assigned to the transportation sector. If this approach were used, the Frontier Oils are, by comparison, massively overpriced.

As regional development incentives, each job in Hibernia will cost approximately $4 million; each job in the "In-Situ" Sands will cost approximately $1.5 million. Jobs in ethanol production would cost approximately $100,000.00 each. Ethanol production has not been accorded equivalent treatment.

It would appear more appropriate to call "Bids" for "New Reserve Development" as proposed by Husky to introduce legitimate private sector copetition.

World Markets - There is a Reality!

- In world markets, supply / price relationships will dominate; e.g. there is now evidence that OPEC may have followed rather than led the market in the late 1970's (Fig. 5).

- In a surplus market, the low cost producer can set the price as has been demonstrated by Saudi Arabia.

- OPEC will inevitably control the world oil price, probably within 5 to 7 years. This organization well understands the role "Random" pricing can play in restricting the extent of new supply development while optimizing its long term profits.

- The development of a viable "clean" fuel would almost certainly dislocate the current oil pricing structures.

SUMMARY

General

- There is no evidence that massive world oil price increases would be sustainable.

- Long term oil prices will likely be set by OPEC or the markets to restrict new reserve development.

- A competitive non-polluting fuel with a broad resource base must be developed to maintain economic growth in the developed nations and to dissuade underdeveloped Nations from pathways solely dependent on conventional hydrocarbons.

Economics

Ethanol from biomass represents:

- A potentially massive industrial opportunity as well as an opportunity to end both energy and agricultural subsidization.

- A strong deflationary influence on oil pricing.

Environment

- Ethanol is unique amongst the liquid fuel options as the only practical fuel to mitigate the "Greenhouse" Effect.

Appropriate Action

Appropriate action for a responsible Canadian role should be as follows:

Environment

Endorse US EPA ambient air quality standards to assure that pollution is no longer treated as a profit centre.

Initiate a firm, attainable schedule on CO_2 emissions reduction.

Require that all new cars be flexible fuel by 1995, to expand the government options for future transportation fuels and to permit attainment of any CO_2 standard decided upon.

Redistribute our energy research budget with more appropriate balance to reflect the "Sustainability" imperative.

Target environmental research support towards industrial opportunity.

Economic: - Remove Institutional Barriers

Treat "Clean" fuels equivalently to Frontier Oils.

Encourage tax "Flow Throughs" for clean fuels to assure improved industrial diversity in the supply sector.

Mandate "Clean" fuel market entry at "Rack" value similar to the electricity "Entry" requirement.

Expedite reciprocity for fuel ethanol under F.T.A. to encourage a Canadian industry. Concern currently exists that the benefit of Canadian subsidized Frontier oil will accrue to the United States while our ethanol is excluded from United States market incentives.

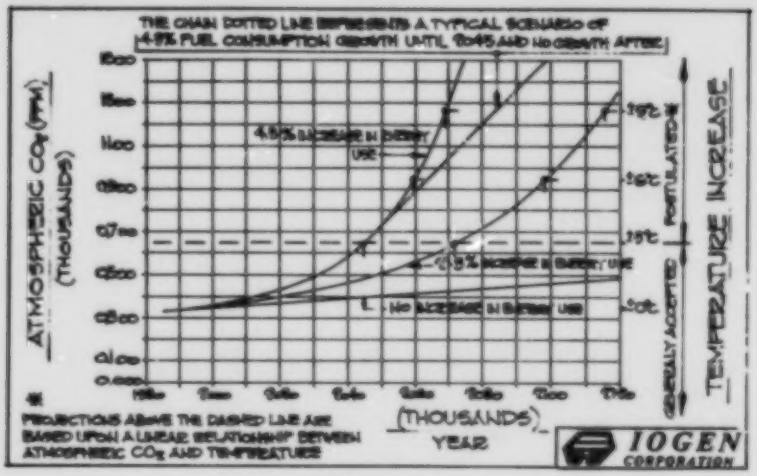


Figure 1

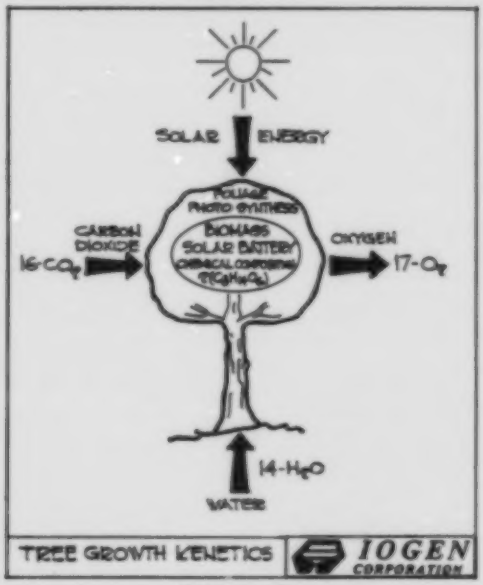


Figure 2

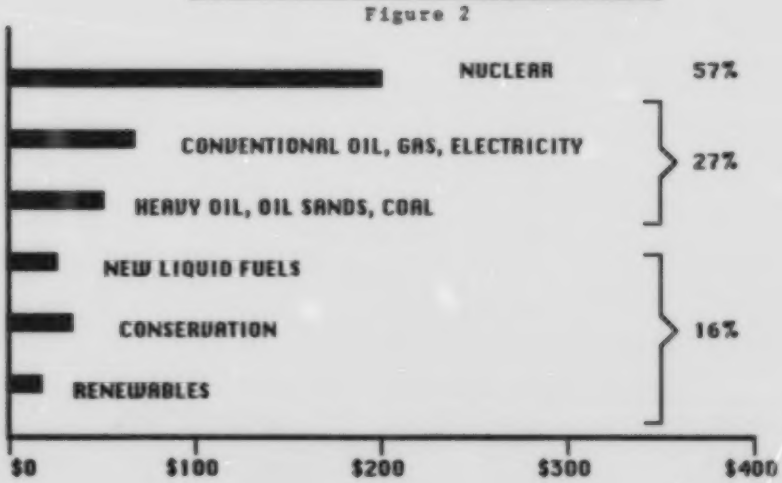


Figure 3

Canadian Supply and Demand
Crude Oil and Equivalent

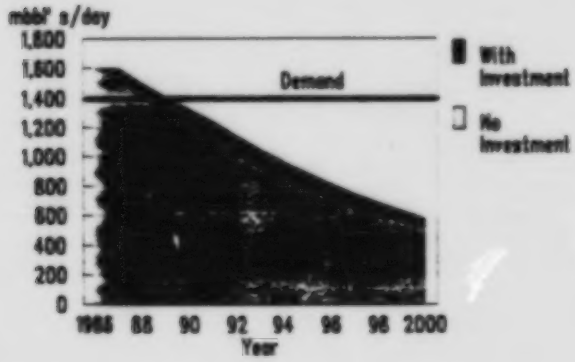


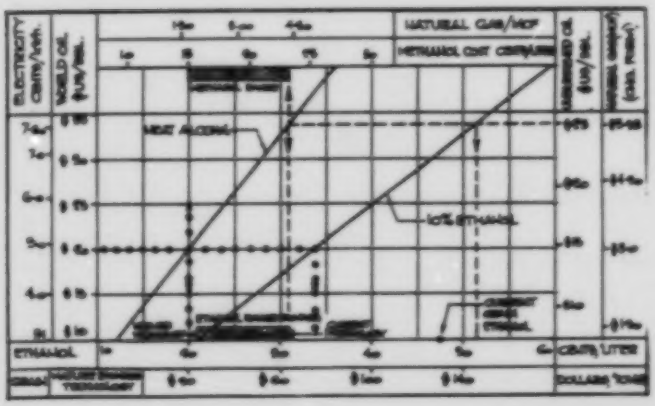
Figure 4

FUEL VALUE COMPARISONS (I)

Basis Rack Gasoline

Fuels:- Oil - Ethanol - Methanol (Natural Gas)

Electricity - CNG



All Prices Basis "Rack" or Wholesale

Figure 5

PROSPECTS FOR BIOENERGY IN 2010

Brian Emmett

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Ottawa, Canada

INTRODUCTION

I have been asked to address the somewhat intimidating topic of the prospects for bioenergy in the year 2010.

The events of the past two decades have revealed the perils of energy forecasting. Indeed, if we have learned anything from that experience it must be that individual forecasts of energy production, consumption and prices are certain to be off the mark. The challenges of foreseeing the energy future consistently defeat all of the combined skills and artfulness of industry experts, economists, and statisticians alike.

Nevertheless, we can start from some fairly basic propositions in looking at the future: The market penetration of bioenergy will be determined to a very large extent by its competitiveness with other fuels in those areas where it is technologically possible to substitute bioenergy for them. The competitiveness of bioenergy will depend on the cost of producing and using bioenergy for a given application relative to the costs of using alternative fuels in the same application, as well as the quality and convenience of competing fuels.

There will be many determinants of such costs, including the technology of energy using equipment, advances in production technology for different kinds of energy, and, of course, the market price at which alternative forms of energy are made available. Regulatory systems and public perceptions concerning fuel usage and environmental protection will also have a major impact on the choice of fuel. A major and sustained increase in the price of oil would provide a significant impetus for enhanced reliance on biofuels, for example.

Given the perils of forecasting, I have chosen to approach this topic in three parts. First, I will discuss briefly the evolution of biomass as a fuel in the past, concentrating on the economic and technical factors which have affected its market share. Second, I will summarise briefly the forecasts prepared by the National Energy Board (NEB) in 1988 of supply and demand for energy in Canada in the year 2005 with particular emphasis on the role seen for biomass. Third, I will discuss some of the factors which may lead to departures from the NEB's surprise-free scenarios and lead to significant changes in the role of biomass.

EVOLUTION OF BIOMASS AS A FUEL

[Only passive solar energy can claim to have played a larger role in meeting human needs than energy from biomass.]

Biomass from wood, dung, and agricultural wastes was the dominant fuel in all early societies and retained its strangle hold on energy markets until relatively recent times in historical terms. Nevertheless, competition for market share is by no means a recent phenomenon. By 6000 B.C. asphalt had been used as a fuel by the Sumerians. In Babylonia, asphalt and crude petroleum were used as fuels in preference to wood. Somewhat later, (c. 1100 B.C.) the Chinese became the first society to mine and use coal. By 1000 B.C. the Chinese had also developed the technology to drill gas wells and to transport the gas by bamboo pipelines. Coal was later used for industrial purposes in Greece (c. 400 B.C.) and later still by the Romans in Britain.

Earlier competitors to biomass encountered some problems familiar to those of you who have tried to market new energy products - institutional barriers and consumer resistance. For example, in 1306 King Edward I made it a capital offence to burn coal in Britain, on the basis that its combustion gases had been found to be poisonous. At least one man was executed for burning coal.

By the early part of the 17th century, the insatiable demand for wood as a fuel and raw material had led to the virtual deforestation of Britain, and forced a partial substitution of coal for wood in some applications. By 1700, the commercial use of coke for blast-furnace operations was firmly established, and coal was tolerated in spite of its smoke and odour. Space heating and process heating continued to be dominated by wood until the mid-19th century. Cost and availability of supply as well as technology of end use was already having an impact on market share.

Figure 1 shows the evolution of world market shares by fuel type over the last 150 years. As recently as 1880, coal and wood were the only significant fuels, and it is only in the post-1880 period that fossil fuels have come to displace biomass as the world's dominant source of energy.

The long run change in the relative market shares of different fuels over the last century and a half can be explained by the emergence of new production technologies which made it possible to produce hydrocarbon fuels at very competitive costs, and by the emergence of new energy consumption technologies which demanded the flexibility and energy density which liquid hydrocarbon fuels had to offer.

The very dramatic increase in the market share accounted for by oil can be explained to an extent, by the historical series on oil prices contained in Figure 2. The real price of oil fell from a high of $35 U.S. a barrel ($1982) to less than $10 a barrel within a 15 year period. Over the last 80 years, the average real oil price has remained in the range of $12 a barrel although there have been pronounced cyclical movements around the price. For most of this century, oil has been a very cheap, flexible, and reliable fuel. These characteristics enhanced its market acceptance and enabled it to gain market share at the expense of coal and wood, which were traditional, but less convenient fuels. The very rapid price escalation for oil which occurred in the 1970's and early 1980's reversed this trend. Oil came to be regarded as a very expensive fuel, with questionable security of supply. This gave rise to major efforts to find a replacement fuel, and stimulated much of the reawakened interest in alternative fuels, including bioenergy.

Figure 3 shows the evolution of renewable energy use in Canada over the last hundred years or so. In 1870, wood provided for nearly 90% of all energy consumption in Canada. By 1900, wood accounted for less than 50% of Canadian energy needs, and by 1965 its role had declined to the point where it supplied only 2.5% of Canadian energy requirements. Since then, the importance of wood energy has expanded in both relative and absolute terms to the point where it supplies 5 or 6% of Canadian energy consumption.

BIOENERGY TECHNOLOGY AND APPLICATION

Compared to fossil fuels, biomass has a low energy density, high moisture content, extreme particle size variation and low heat combustion. Hence, in most applications, biomass requires an upgrading of the quality of the raw material before it is used as a fuel. This transformation can be achieved by means such as pulverization, drying and densification, pelletization, or through chemical conversion. These processes bring cost savings in transportation, handling and pollution controls.

Direct combustion was the earliest process for converting biomass into energy and is still the most common usage of biomass around the world. Development of new technologies has significantly improved the energy efficiency of combustion processes. Systems now vary greatly in size and complexity, from manually fuelled domestic stoves to computer controlled industrial hog-fuel power boilers to provide steam, heat, or electricity. Technology recently developed could allow the production of electricity with thermal power from burning whole trees.

Through gasification, wood can be converted into a flexible fuel gas. The synthesis gas produced can be used in a great variety of applications. In addition, the chemical composition of the gas can be adjusted to allow synthesis of methanol.

Biomass can be converted to alcohol by natural fermentation or chemical conversion. Alcohol fuels have a long history. Because it was clean and odourless, alcohol fuel replaced whale oil in lamps in the mid-1880's. The first modern internal combustion engine, the Otto cycle engine built in 1976, could run on either ethanol or gasoline. Henry Ford designed the Model A and the Model T with adjustable carburetors, permitting them to run on gasoline, ethanol, or any combination of the two. During the 1920's and 1930's, New Zealand used ethanol as its primary automotive fuel. The onset of World War II increased the interest in alcohol fuels. The German army fuelled many of its vehicles with ethanol made from potatoes.

NATIONAL ENERGY BOARD SUPPLY AND DEMAND FORECAST

Figure 4 presents the National Energy Board (NEB) high and low projections of end use demand by fuel in Canada to the year 2005. The low case assumes low economic growth internationally, which leads to a modest increase in demand for oil. Because the demand for oil does not rise very rapidly, oil prices in this scenario are assumed to increase slowly from $U.S.15 a barrel in 1988 to $U.S.20 a barrel in 2005, all measured in terms of $1987. The high case assumes world economic growth will be considerably stronger at 3% per year. This high growth leads to a higher demand for oil and causes the oil price to rise more quickly - oil prices reach a level of $U.S.30 a barrel by 2005.

Renewable energy is defined by the NEB to include wood, wood wastes, municipal solid wastes, solar energy and wind energy. In practice almost all renewable energy used in Canada is wood or wood wastes. Of 522 petajoules of renewable energy consumed in Canada in 1986, wood wastes consumed by the pulp and paper industry accounted for 410 petajoules. Wood use in the residential sector accounted for a further 110 petajoules, leaving only 2 petajoules for all other sources of renewable energy combined.

In both the high and low cases, the share of bioenergy is expected to remain roughly stable at 7% to 8% of the final demand over the next 20 years. In absolute terms, the use of bioenergy to supply primary energy needs is expected to

increase by about 150 petajoules. Figure 5 illustrates the slow but steady growth which is expected in total Canadian consumption of renewable energy, which will be virtually all biomass until the year 2005.

REGIONAL DISTRIBUTION OF BIOENERGY

Since bioenergy in Canada is mostly derived from wood wastes produced by the forest products industry, it is not surprising that those areas with the greatest concentrations of the forest products industry are the same regions which have the greatest reliance on bioenergy. Figure 6 compares the percentage importance of renewable energy in each Canadian region in 1986, with the NEB's projection of its fuel share by region in 2005. Bioenergy utilization will continue to be highest, in percentage terms in Atlantic Canada and in British Columbia.

Figure 7 shows that the NEB does not project that radical new uses of bioenergy will emerge within the time frame of its current forecast. The figure also shows that by far the largest user of wood fuels in Canada will continue to be the west coast forest products industry, followed by the forest products industries of Ontario and Quebec. The figure also shows that industrial utilization of wood fuels will remain greater than residential use in each region of the country, and that the highest ratio of residential to industrial use will continue to be in the Atlantic provinces.

SENSITIVITY OF NEB PROJECTIONS ON BIOENERGY

The NEB forecasts provide a very useful starting point for an assessment of the role of bioenergy in the energy economy post-2000. They essentially pose the question: What is the likely role of biomass given a continuation of the technological relationships which characterize the economy today; given two alternative assumptions regarding orderly continuous increase in the prices of competing forms of energy; and also given that the policy environment does not change in some fundamental way.

The model indicates that under these conditions, demand for bioenergy will grow in absolute terms but its market share will not increase. This can largely be explained because bioenergy does not penetrate new markets outside forest industries and residential home heating. This is partially a result of the NEB's forecasting methodology which is not well suited to handling penetration of entirely new areas and partially by economic and technical judgments built into the assumptions underlying the projections. Thus growth in biomass use will be closely linked to forest products. This particular sector is facing stiff competition from developing countries - and technological change in Canada is increasing the amount of the tree used for pulp and paper leaving less waste available for fuel. These developments will tend to dampen potential growth in bioenergy use in the forest product sector.

With bioenergy at or near saturation in the forest products industries and in existing residential uses, bioenergy must look for growth to the transportation sector, to electricity generation and to other areas. As the NEB forecasts indicate, big increases in bioenergy use in these areas are unlikely in the absence of an increase in the price of other fuels; technological breakthroughs which reduce costs and increase ease of use and/or significant changes in policy which would promote biomass over competing fuels.

All these changes are possible. Indeed, our experience from OPEC to cold fusion led us to expect the unexpected. Since I agree that the NEB oil prices scenarios likely bracket what is sustainable over an extended period, let me turn to a more bottom-up examination of biomass in electricity generation; in transportation; and in other areas.

Electricity

The NEB shows demand for electricity increasing more rapidly than the demand for other fuel types. Electricity is expected to hold or increase its market share - and grow in absolute terms. This will confront utilities with difficult choices about meeting future demands for electricity with hydro, coal, gas, nuclear energy, alternative energy and demand side management. Choices will involve a difficult balancing act between economic considerations, environmental impacts and public acceptability.

Utilities are increasingly turning their attention to examining innovative means of meeting load growth including demand side management, independent power production, cogeneration, and the use of bioenergy. There are now roughly 3,500 MW of biofueled electrical generating capacity in place in North America. Utilities may well add to this capacity but will want to ensure that reliance on biofuels would not be more expensive or problematical from an environmental or reliability perspective than the coal or nuclear alternatives.

For biomass, economics will be a key consideration and coal a key competitor. Forecasts generally indicate that the present state of overcapacity in coal production is likely to be maintained for the foreseeable future, and this is liable to keep coal prices at present levels in real terms for many years. Bioenergy is likely to make significant gains relative to coal only in those areas which do not have easy access to abundant supplies of biomass fuel.

New Brunswick power has commenced work on a wood burning prototype, and the progress of this unit will be watched with interest by utilities in other provinces where wood industries are relatively important.

Transportation Fuels

Bioenergy has a potential role as a transportation fuel, through the production of ethanol and methanol as gasoline additives. For Canadian climatic conditions it is possible to visualize concentrations of up to 10% alcohol in automotive fuels. In some countries this is already a reality. There could be a potentially huge market for alcohol as a transportation fuel in Canada. For example, the NEB high forecast suggests Canadians will use 37 billion litres of gasoline annually by 2005. If 10% of this could be replaced with ethanol, there would be a domestic market for 3.7 billion litres of ethanol - more than 40 times Canada's total ethanol production capacity in 1986.

This level of market penetration for ethanol would require the solution of some technical problems relating to engine performance. It would also require significant advances in ethanol production technology leading to lower unit costs. Even if these occur, the continued availability of inexpensive oil will set a ceiling on the price that can be charged for alcohol fuels. Production of biomass for conversion to alcohol fuels would be more expensive in Canada than in countries such as Brazil because of shorter growing seasons and cold winters which are characteristic of Canada. It is unlikely that the ceiling price established by competition from oil would be high enough to cover the full cycle cost of major new alcohol production facilities in Canada, without a major change in technology or a major sustained increase in the price of oil.

ENVIRONMENT CONCERNS IN THE MARKETPLACE

Biofuels are not completely non-polluting, but there is significant evidence that their effects on the environment may be more benign than the fossil fuels they compete with. The environmental problems of coal mining and oil production in terms of waste water disposal, leaching of acids, chemicals, and heavy metals into groundwater, and contamination of the environment through fugitive dust or oil spills are well known. These problems are absent from biomass production and the problems which may be raised by commercial production of biofuels, such as soil erosion, seem to be easier to prevent, control, and contain. In addition, the combustion of biofuels does not release acid gas into the atmosphere, and tends to be less polluting than fossil fuels in other respects as well.

The increased concern about the environment has yet to be reflected in the relative price of alternative fuels. If such concerns were captured by relative prices, the price of polluting fuels would tend to rise, and the price of those fuels which are less polluting would tend to fall. If the environmentally induced price change were large enough, this might be sufficient to shift the balance in the choice of fuels, at least in some selected instances.

In the absence of environmentally driven changes in relative prices, perhaps the best environmentally-related prospects for increased use of bioenergy are in the area of municipal solid waste disposal. The cost of using landfill as a waste disposal technology has been increasing, and indications for the future are that this cost will increase even more sharply, especially for large cities such as Montreal and Toronto.

Incineration of municipal solid wastes presents an alternative approach to this problem that may be more acceptable from an environmental and land use perspective. New technologies have been developed to sort and incinerate wastes in a way which does not release poisonous compounds to the atmosphere, although the problem of emission of greenhouse gasses remains unsolved in this application as it does for all combustion processes.

Since the wastes are burned primarily to reduce their size and toxicity, the energy produced by the process may be regarded as a free good. Any price that can be obtained for this energy will contribute to covering some of the costs of the incineration activity, which would in any case occur even if the energy by-product could not be sold.

This puts energy from municipal waste disposal in a favourable position to compete with other forms of energy. The real costs of other fuels are expected to drift upwards over time. For municipal solid wastes, the opposite is true. The availability of this form of waste is definitely on the increase as is the cost of disposing of it through means other than incineration. This should increase the attractiveness of incineration as a waste disposal approach, and therefore increase the number of instances where heat generated as a by-product of waste disposal will be available to meet the energy needs of urban areas.

Incineration of municipal wastes is not yet a major factor in Canadian bioenergy production. There are at present only a few facilities in the country dedicated to this purpose, and landfill is still very much the dominant way of disposing of urban waste.

As Canadian urbanization increases and the size of major centres continues to grow, it is likely that increased pressures will mount on urban centres to view municipal solid waste as an environmentally acceptable fuel source rather than as a waste disposal problem.

SUMMARY

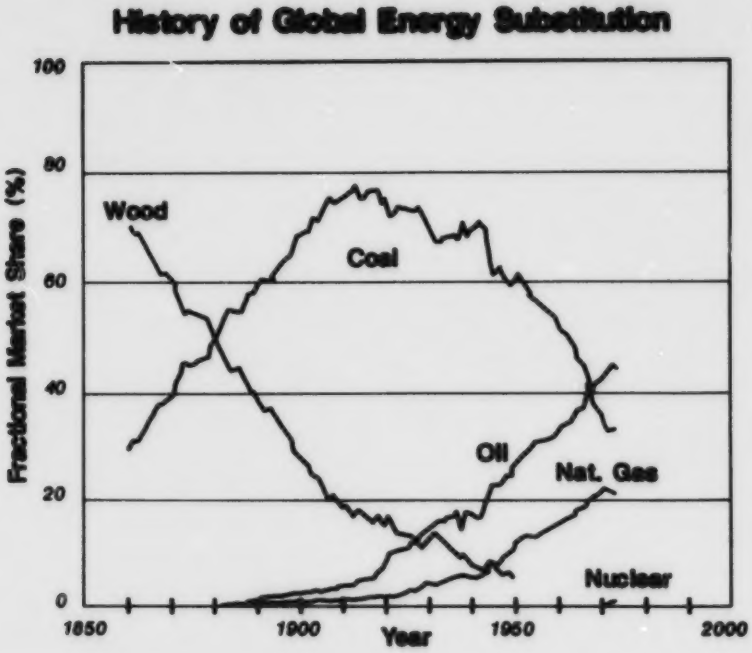
Figure 8 summarizes prospects for biomass fuels in Canada over the coming two or three decades. Wood wastes will continue to be used as industrial fuels by the forest products industry. Electric utilities will continue to be interested in the possibilities of wood wastes for relatively small scale generation in those areas which have heavy concentrations of wood industries, and which

might therefore produce wood wastes surplus to the wood industry's own fuel requirements.

Use of firewood as a residential heating fuel is expected to continue, but this can be regarded as a mature market. Such usage will be based on local availability and preferences and is unlikely to experience any dramatic shifts within the time frame we are discussing.

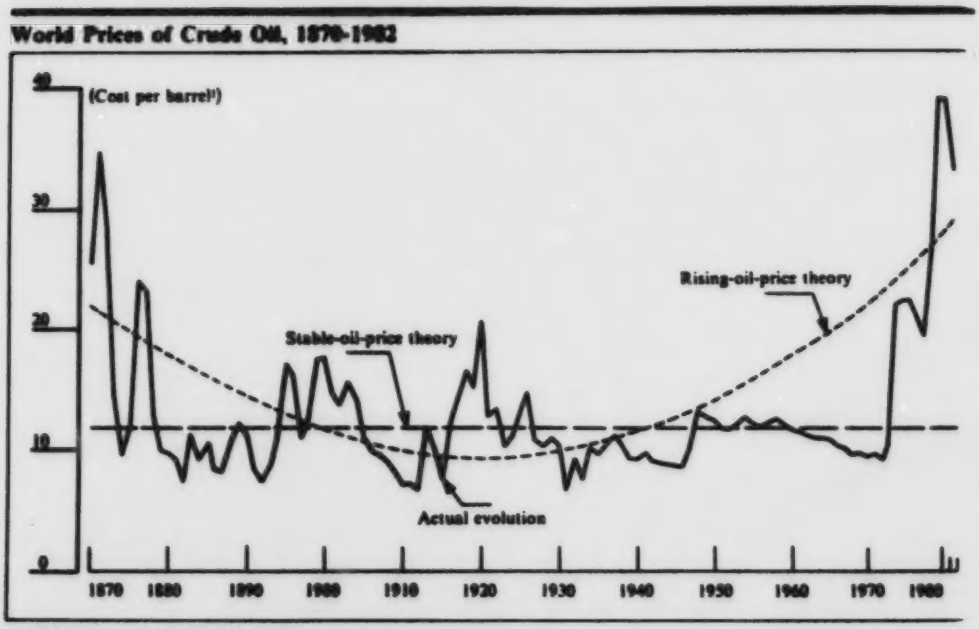
A large scale increase in commercial production of alcohol fuels for transportation in Canada over the coming two or three decades is possible but will face stiff competition from hydrocarbons which are expected to remain abundant in supply and relatively low in cost in the near medium term. Our concerns about an approach to security of supply has also changed significantly over the last several years. I do not see major departures from our market-based energy policy for security of supply reasons in the foreseeable future.

Increasingly, municipalities will come to view their solid wastes as a potential fuel, rather than as a tiresome disposal problem. This is one application where both economic and environmental forces will give new impetus to expanded commercial use of bioenergy.



SOURCE: International Institute for Applied Systems Analysis

Figure 1



1 Measured in constant 1982 U.S. dollars.
SOURCE: Bourque, "Évolution du prix international du pétrole."

Figure 2

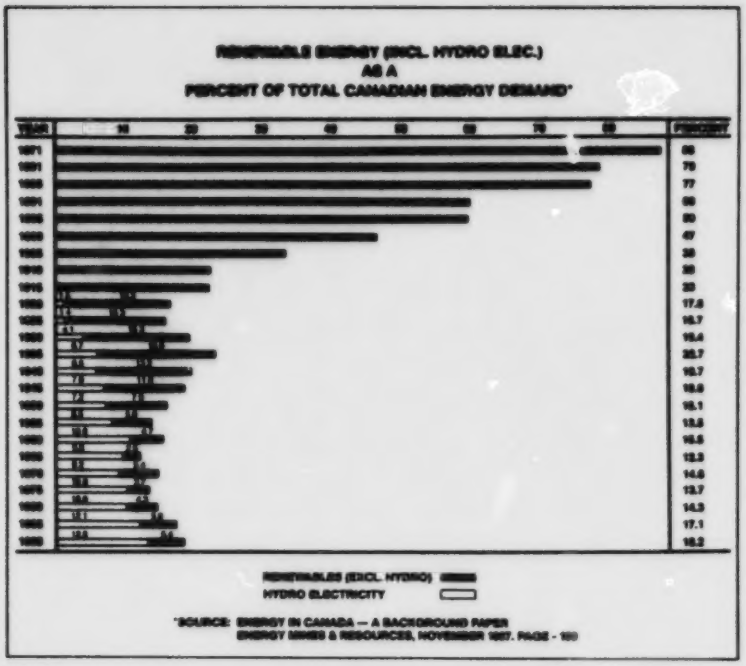
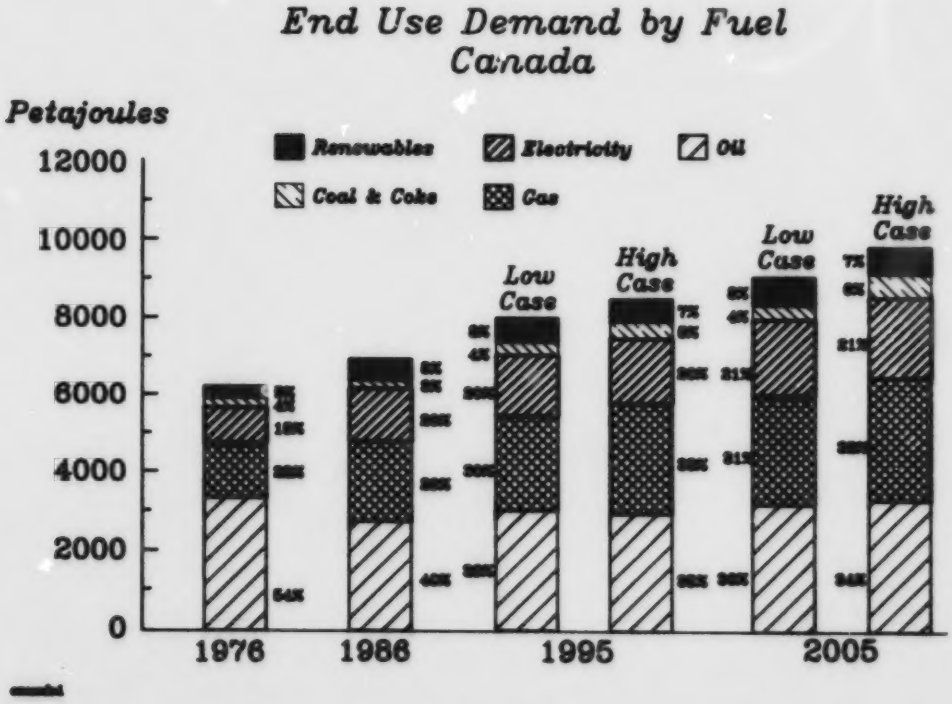


Figure 3



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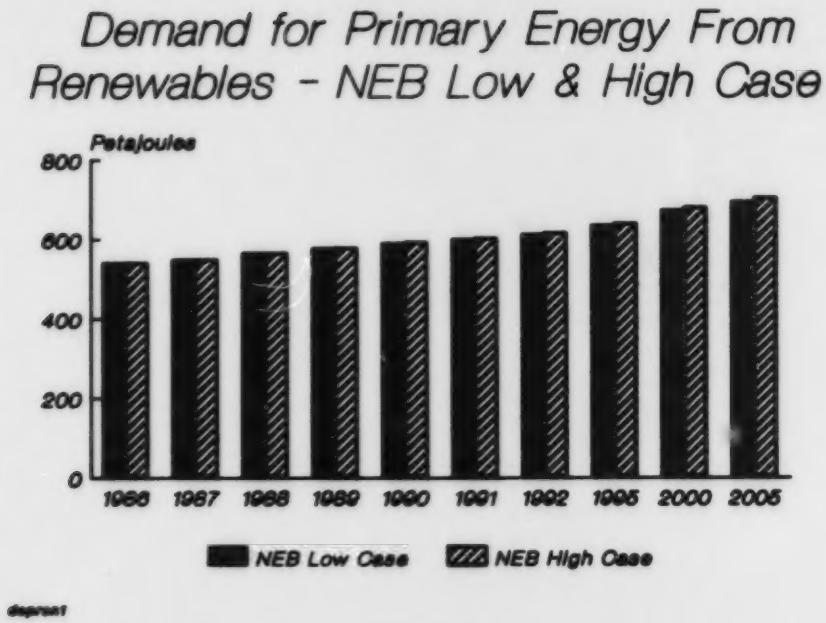

Figure 5

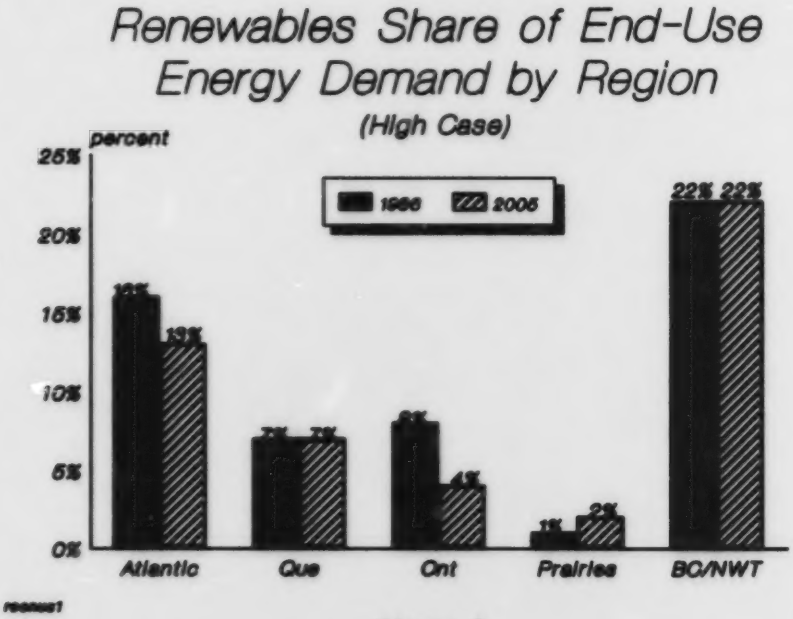

Figure 6

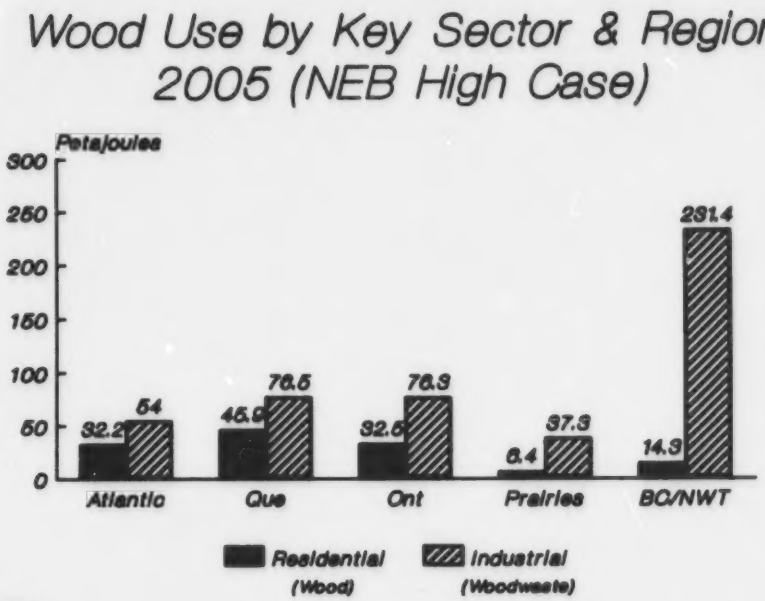

Figure 7

SUMMARY PROSPECTS FOR BIOENERGY IN CANADA

Wood waste	Process heat and steam Electricity cogeneration	Will remain very significant in forest products industry Interest in prototypes by utilities	Technical change reducing waste component of tree
Wood chips or pellets	Electricity generation	Increasing interest	Technological progress Cost of alternative fuels
Residential wood	Space heating	Little change	
Alcohol fuels	Transportation fuels	Continued limited aplication in Canada	Present and anticipated low oil prices provide little incentive for investment in this technology Scope for major advances in technology, cost competitiveness
Municipal solid waste	District heating Electricity cogeneration	Significantly increased usage	Environmental pressure Availability of landfill sites Technical progress in producing and burning wastes Prices for recycled metals and minerals Cooperative actions by municipalities and utilities

Figure 8

CRITICAL ISSUES IN BIOENERGY DEVELOPMENT: PRICES AND PROSPECTS THROUGH 2010

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Bioenergy is a significant, established component of Canada's energy mix. The contribution of bioenergy to primary energy demand in Canada is estimated at 8-10 percent, and a substantial, sustainable biomass resource is available for expanded energy supply. The development of bioenergy in Canada has been strongly influenced by developments in fossil fuel prices. This was particularly evident over the last 15 years, when bioenergy development waxed and waned with movements in crude oil prices and world oil market conditions.

This paper will extend this theme by presenting reasonable scenarios for crude oil prices through 2010 and offering some observations on energy-use patterns given these projections. Based on these scenarios, a number of observations will be drawn as to the likely role for bioenergy in Canada, and the technologies with the greatest potential for market penetration. The central conclusion of the analysis is that (i) based on project economics alone, bioenergy development will continue to be selective and gradual; and (ii) environmental legislation (short of draconian measures aimed at dramatically reducing hydrocarbon combustion) may act to worsen bioenergy project economics, rather than providing a strong push for market penetration.

1. INTRODUCTION

The reality of crude oil in the world energy market is such that the price and availability of crude oil will continue to determine, in large part, the speed of development and degree of penetration of, among others, bioenergy within Canada's sources of energy supply. Technology development and technical innovation must be viewed in the context of economic considerations. It does little good to develop a new idea if it will not survive the test of the marketplace and perform a desired service at lower cost than available alternatives. Energy technology is no exception.

This paper provides some brief comments on the place of renewable energy in the global energy market and, more specifically, in the Canadian energy market. Based on reasonable scenarios for future crude oil prices, the paper concludes with a number of comments on the likely near-term and medium-term opportunities for bioenergy in Canada.

2. RENEWABLE ENERGY IN THE WORLD ENERGY MARKET

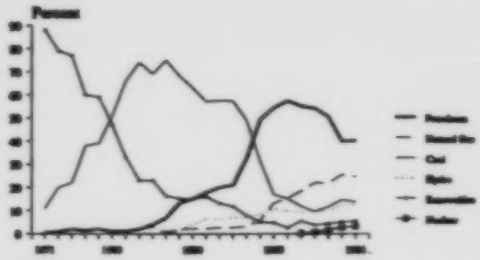
The revolutionary developments in global trade and commodity transportation witnessed during this century gradually transferred the emphasis of determination of energy supply sourcing away from indigenous resources and towards the degree of industrialization and economic development of a given country or region.

For many of the industrialized countries, the pattern of energy use has paralleled that of Canada. Figure 1 shows the four key phases of energy use in Canada; first, an extended period of dependence on renewable energy, largely wood, followed by the displacement of renewable energy sources by coal in the early 1900s, and that by the rise to preeminence of crude oil as our primary energy source. The fourth phase, in which Canada and most of the industrialized countries currently reside, has been termed by the Japanese the Multiple Energy Era. Indeed, it is the opinion of many energy market analysts, and one shared by CERI, that the next twenty to thirty years will be characterized by the absence of a dominant energy source. Rather, we will witness increased competition at the burner-tip among various energy sources, and the pursuit of numerous energy options, aimed at avoiding reliance on imported energy and maximizing our ability to respond to relative price changes among energy sources.

In other countries around the world, the move toward alternative sourcing of energy has proceeded at a widely differentiated pace, largely dependent on the economic resources of the country, the indigenous energy mix, and the political imperatives of environmental concern and exposure to a volatile and unpredictable world oil market.

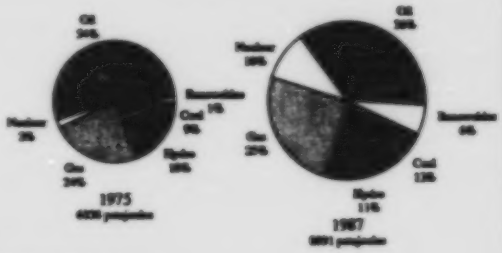
In Brazil, virtually all of the automobiles currently produced are designed to run on a "neat" ethanol fuel, containing 80% ethanol.

Figure 1
Primary Energy by Source, Canada
1871 - 1986



SOURCE: Energy, Mines and Resources Canada, Energy in Canada: A Backgrounder Paper, November 1987.

Figure 2
Fuel Substitution in Canada
1975 - 1987



SOURCE: National Energy Board.

Note: Data for primary energy demand.

In China, the environmental consequences of fuelling the coming industrial revolution on coal has yielded a rapid deployment of all available renewable energy alternatives, including what is the worlds largest utilization of solar energy technology.

In India, the pursuit of bioenergy is expected to take a considerable share of the refined petroleum products market by the turn of the century.

In Western Europe and North America, the rapid ascendence of environmental issues to the top of the energy agenda will see tremendous changes in how these economies use energy, changes which will have significant implications for the renewable energy sector.

While availability and development of alternative energy supplies will be critical to the Multiple Energy Era, much of the adjustment will be seen on the demand side of the equation and, in particular, the ability of energy users to switch away from refined petroleum products and toward alternative sources of energy. In Canada, the degree of fuel substitution over the last decade has been remarkable (see Figure 2). Crude oils' share of primary energy demand has declined from 54% in 1975 to 36% in 1987. Of note here is the significant growth in renewable energy consumption, along with electricity and natural gas, over that period.

The time frame shown on this slide is particularly important, and brings me to the main thesis of my remarks today. The development of alternative energy sources and the speed of adoption of those energy sources over the last 15 years has been closely tied to the ascendence of OPEC in the world oil market and the dramatic price increases in world oil over the 1970s and early 1980s. In many respects, the resurgence of, in particular, coal and renewable energy sources in the world energy mix is the direct offspring of OPECs success in driving up the real price of crude oil.

High crude oil prices created the economic environment which allowed for the development and deployment of new technologies, and the redeployment of old technologies, which brought forth the plethora of energy alternatives which we have at our disposal today.

Similarly, an extended period of low oil prices will have the opposite effect, depressing project economics and removing the commercial and political imperative for pursuit of these higher-cost alternative energy sources.

This is the economic reality of the world energy market today. Crude oil, which continues to possess the desirable properties of easy transportation, relatively clean combustion, and (currently) low prices, remains the benchmark against which energy options and alternatives are assessed. And, having created the undesirable offspring of readily available energy alternatives, it is clearly in the interests of OPEC, and oil producers in general, to attempt to maintain a price level which will discourage the further development of these alternatives.

Having put forward the importance of the role of world oil prices to the development of alternative energies, what then can we say about the future of world oil prices?

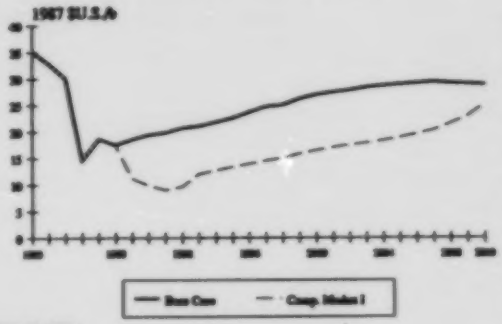
3. CRUDE OIL PRICES: SCENARIOS FOR THE FUTURE

Over the last few years, the Canadian Energy Research Institute has developed a powerful analytical framework designed to investigate various scenarios for the world oil market. This tool was used to analyze the scenarios discussed below.

In examining future oil price trends, it is necessary to focus on the fundamentals of the world oil market. In determining likely market prices, the cost of crude oil is an important variable. Table 1 provides crude oil replacement costs for the non-OPEC producing countries. The first observation is that replacement costs (defined as exploration and development costs per barrel of reserves) are on average, well below current market prices for crude oil. This suggests that current levels of non-OPEC production could be maintained for some length of time at low oil prices; stated differently, the oil market will be slow to adjust to low prices without production restraint by oil producers. Second, Canada and the United States are among the highest cost producing regions in the world, due to a combination of relatively low finding rates and flow rates per well (characteristic of mature basins). North America clearly requires strong crude prices to maintain domestic production.

Given realistic assumptions regarding production levels for OPEC over time, non-OPEC supply potential, economic growth rates around the world, and the responsiveness of oil demand to changes in price and economic growth, the Reference Case Scenario shown in Figure 3 provides a readily sustainable price path for crude oil over the next 20 years. The principal trend is for slowly rising real oil prices through to the mid-1990s, followed by slightly accelerated increases over the next 5 to 6 years. Prices reach $22.50 per barrel in 1995 and exceed $27.00 per barrel by the year 2000. Thereafter, the growth rate in real crude prices is slowed considerably by the combined forces of alternative energy development, non-conventional oil sourcing, and increased flexibility in end-use energy demand. In this scenario, prices peak at under $30.00 per barrel and enter a gradual decline by the end of the forecast horizon.

Figure 3
Crude Oil Price Projections



SOURCE: CERI.

This price projection provides a very realistic picture of future oil market developments. The level of crude oil production assumed for OPEC allows for gradual relaxation of current production quotas and should be sustainable with a reasonable degree of cartel unity. Steady demand growth and an eventual decline in non-OPEC production will allow OPEC to gradually increase both its market share and annual revenue. Over the longer term, readily available alternative energy sources and technologies place a ceiling on the crude oil price projection.

TABLE 1

CRUDE OIL REPLACEMENT COSTS IN THE NON-OPEC COUNTRIES

	Percentage of Production Onshore	Projected Finding Rates as of 1987 (b/ft.)	Weighted Average Flow Per Well (b/d)	Weighted Average Producing Well Depth (feet)	Replacement Costs as of 1987 ($1985 U.S./bbl)
Angola	31	329	1,010	5,237	9.98
Argentina	100	29	77	8,039	11.60
Australia	12	97	4,646	7,330	21.46
Brazil	28	128	2,435	3,869	12.96
Canada	100	14	96	5,189	11.80
Colombia	100	103	968	8,347	4.83
Egypt	25	405	3,148	6,156	9.09
India	100	126	338	4,810	9.20
Malaysia	41	280	1,132	5,424	8.31
Mexico	34	1,184	11,600	12,051	4.66
North Sea	0	365	7,217	8,503	11.67
Other Middle East	95	370	1,459	5,799	2.50
United States	82	10	131	10,390	13.50
Western Europe	53	32	4,413	5,654	9.92

SOURCE: Canadian Energy Research Institute.

The other side of the coin is a Competitive Market Scenario, based on a breakdown of OPEC in 1989 and the development of a non-cartelized world oil market. OPEC member countries are assumed to return to previous productive capacity by 1993, phased in according to the amount of time required to achieve this level of production in the various countries. OPEC production reaches 33 MMb/d by 1993, with an additional 1 MMb/d of productive capacity assumed to be brought onstream in each subsequent year, centered in the reserves-rich Persian Gulf region.

As shown in Figure 3, the impact of the competitive market scenario is dramatic. The real world oil price quickly falls to an average of just over $11.00 per barrel in 1989, with a further decline to $9.00 per barrel by 1991. In 1993, after four years of very low oil prices, a huge surge in oil consumption becomes the dominant feature of world oil trade, and prices begin to recover. Prices rebound to $16.00 per barrel by 2000 and reach $25.00 per barrel by the end of the forecast period.

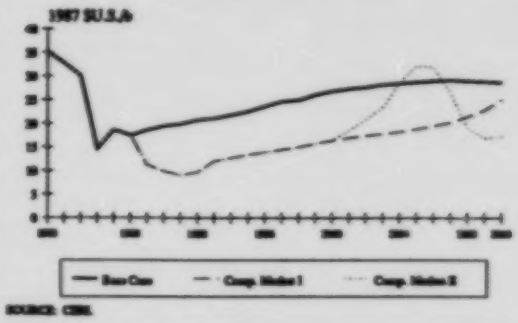
Dramatic as these developments are, our estimate of the competitive floor for oil prices is somewhat higher than other estimates. The result, of course, is critically dependent on the speed of development of the massive Middle East reserves. If the OPEC taps could be opened more quickly, then the floor price could well prove to be lower.

Indeed, one would expect to see downward price spikes, of short duration, to reach well below the $9.00 per barrel mark, due to market overreaction to the collapse of the cartel. It is instructive to note that the price crash of 1986, which saw $10.00 per barrel crude oil prices, still yielded a 1986 annual average W.T.I. price in excess of $14.00 per barrel.

An alternative view of this competitive market scenario is provided in Figure 4. In this scenario, a new OPEC emerges near the end of the 1990s and, taking advantage of the extended decline in exploration and development activity outside of the non-OPEC countries, contracts production to gain higher real prices. The crude oil price increases rapidly, exceeding $30.00 per barrel by 2005. This ability to achieve real price increases results from both the absence of a rapid supply response from outside the OPEC nations, and the increased consumption of crude oil over the previous decade. In essence, the market resembles that of the mid-1970s, with much the same market response.

As one would now expect, the turnaround in prices is expected to be equally dramatic and much quicker than that witnessed in the early 1980s, as alternative energy sources and non-conventional crude oil technologies are able to be mobilized at a more rapid pace. Prices fall to below $17.00 by 2009 before beginning a gradual recovery. Note that the price floor would likely be above that witnessed in 1986 due to the higher alternative energy cost expected at that time and the significant depletion of low cost reserves during the previous period of low oil prices.

Figure 4
Crude Oil Price Projections
Alternative Market Scenarios



SOURCE: CERI.

A few further observations are useful at this point. First, the present value of the revenue yield to the OPEC member countries under either of the competitive market scenarios is considerably less than under the reference case. With the exception of Saudi Arabia, the increases in oil production are insufficient to offset the decline in prices, yielding a net revenue loss. These losses are greatest for those countries with the least existing surplus capacity and smallest reserves base. These also tend to be the countries with the largest population and most pressing social and fiscal needs.

Second, the possibility of a smaller, more unified cartel developing around the Persian Gulf nations to protect a price floor is somewhat unlikely. Our research indicates that these countries would to better off, from a revenue standpoint, under a competitive market free-for-all than under a production restraint scenario.

Third, the stability of the world oil market may require a solution to the free-rider problem in which non-OPEC countries are able to produce to capacity while OPEC must restrain production to protect the market price. Given the low replacement costs discussed earlier and the advances in seismic and geological technologies leading to the discovery of additional non-OPEC reserves, the OPEC members may be hard pressed to protect even the somewhat conservative real price gains of the reference case scenario. The recent non-OPEC restraint agreement--initiated by Angola, China, Egypt, Malaysia, Mexico, Oman and the Soviet Union--may represent a first step toward a solution to this problem. However, the initiative will almost collapse in the face of accelerated development of alternative energy sources, triggered by the firmer crude oil prices accompanying a production restraint agreement.

4. BIOENERGY IN CANADA: CONCLUSIONS AND KEY MESSAGES

The key messages arising from these results are first, the world oil market will continue to respond to market uncertainties over the short-term, but follow a stable, upward growth path over the long term. This suggests that price instability will likely be greater over the period to 1995 than later in the forecast horizon. Security of supply will likely remain a minor issue over the next decade, given our projections of world crude oil requirements relative to available supply.

Second, virtually all of the short-term price risk associated with the world oil market continues to reside on the downside. The study authors were unable to generate a single, plausible market scenario that resulted in a price path above that of the reference case scenario.

For government policy-markers, the range spanned by these scenarios suggests that great care be taken to give sufficient weight to the risk contained in long-term price projections. The decision to prebuild crude oil production capacity in the expectation of higher oil prices in the future must be couched in the explicit understanding that project economics may not be realized when the time comes to initiate production.

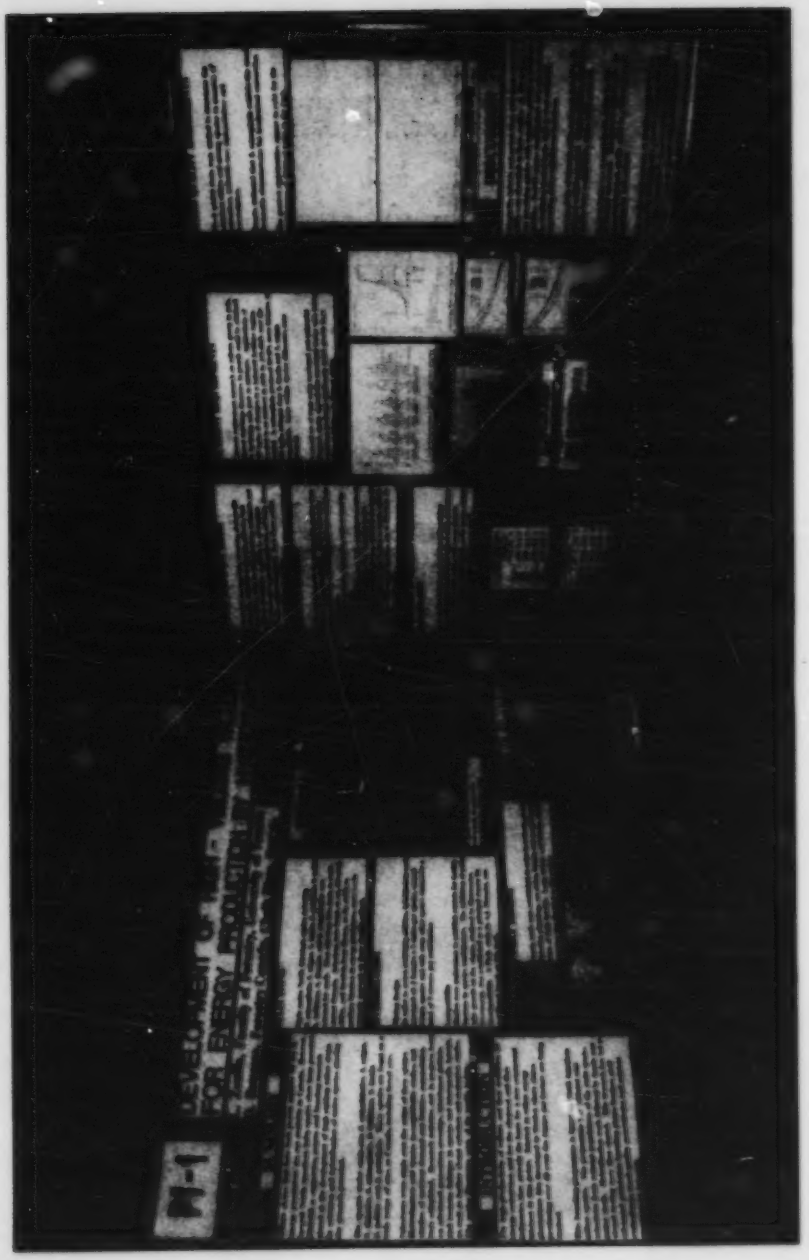
As to the future of bioenergy in Canada, over the last two years CERI has released studies on the future of industrial cogeneration in Canada and on the commercial future for ethanol. In both cases, the economic viability of these technologies is critically dependent on relative energy prices. With cogeneration, it is the low buyback rate on electricity sales, reflecting low avoided cost of power, which places limits to market penetration. With ethanol, it is the low price of refined petroleum products. In general, it is the absence of pressures for energy prices to rise which is curbing the development of bioenergy in Canada. Environmental legislation, to the extent that it operates within the marketplace by altering end-use energy prices, may have the potential to realign these prices and provide a boost to bioenergy development. However, legislation designed to simply curb demand may have the opposite effect, lowering crude oil prices further and weakening project economics.

Having said that, one can isolate some potential winners in the bioenergy area. In the near term, on-site utilization of waste products for electricity generation will continue to be developed, on the basis of economic credits from energy offset and system sales. In the medium-term, both municipal solid waste combustion and ethanol production show significant promise. For the former, the opportunity cost of landfill disposal will continue to escalate, gradually offsetting the project penalties associated with low BTU value and environmental concerns. For ethanol, the combination of lead phaseout in gasoline, tighter CO and SO_2 emission standards, and the continuing disarray in the world agriculture markets all point in favour of further market development as an alternative transportation fuel. Mandated alcohol fuel use in Arizona, California and Colorado provide the precedent for greater ethanol consumption, while supply side research (particularly in cellulosics) continues to lower production costs.

In conclusion, the commercial development of bioenergy in Canada will continue at a steady pace over the next 10 to 20 years, barring a major energy supply disruption or breakthrough. While the abundance of energy supplies in Canada may discourage domestic development, Canadian researchers can make a significant contribution to the world energy market by continuing to lead the development and demonstration of bioenergy technologies.

TEXT OF POSTER PRESENTATIONS

TEXTES DES PRÉSENTATIONS DE SÉANCES D'AFFFICHAGE


W-1
DEVELOPMENT OF
FOR ENERGY

DEVELOPMENT OF HIGH YIELDING WILLOWS FOR ENERGY PRODUCTION BY HYBRIDIZATION

Louis Zsuffa[1] and Darwin Burgess[2]

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Willow clones that have been proven superior for use in energy plantations are not available in Canada. However, several North American species show large potential. ENFOR is supporting genetic and breeding research aimed at the development of high yielding willow clones by selection and hybridization of native species showing the greatest potential.
The species under study are: *Salix amygdaloides, S. bebbiana, S. discolor, S. eriocephala, S. exigua, S. lucida, S. pellita,* and *S. petiolaris*. These species are found on a wide range of sites in Canada, including boreal sites.
Selections were made over the range of these species. Hybridization and species incompatibility studies, and studies of nutrient demand and biomass accumulation, were completed. Research activities now in progress focus on advanced generation crossings, inheritance patterns and isozyme linkages in species and interspecific hybrids, as well as further clonal selection and evaluation studies. The poster illustrates some of the results to-date.

Les clones de saule qui sont supérieurs comme espèces de plantation énergétique ne sont pas disponibles au Canada. Toutefois, plusieurs espèces nord-américaines semblent très prometteuses à cet égard. On parraine, dans le cadre du programme ENFOR, des recherches sur les aspects génétiques et sur le croisement dans le but de mettre au point, par sélection et hybridation des espèces indigènes les plus prometteuses, des clones de saule à haut rendement. Les espèces étudiées sont: *Salix amygdaloides, S. bebbiana, S. discolor, S. eriocephala, S. exigua, S. lucida, S. pellita* et *S. petiolaris*. On trouve ces espèces dans plusieurs régions au Canada, y compris les régions boréales.
Les sélections ont été faites à partir de l'ensemble de ces espèces. On a réalisé des études s'hybridation et d'incompatibilité spécifique, ainsi que des études sur la demande en éléments nutritifs et sur leur accumulation dans la biomasse. Les recherches actuellement en cours portent sur la pollinisation croisée de pointe, les modes d'hérédité et les liaisons factorielles isozymiques chez les espèces et les hybrides interspécifiques et comprennent des études plus poussées de la sélection et de l'évaluation clonale. On illustrera certains des résultats obtenus jusqu'ici au cours de la séance d'affichage.

INTRODUCTION

The high productivity of willows and their usefulness for energy conversion and for the chemical and fibre industries may provide the basis for a new commercial interest in this genus. Interest in willow energy plantations has been expressed in Sweden where clones producing over 40 oven dry tonnes per hectare are being studied (Gullberg 1989).

This breeding programme, consisting of several projects, is based on North American willow species. The programme was initiated with selections from natural populations of the eight species under study. Hybridization work, followed by family and clonal testing, were then started. Information from this research has led to second generation breeding plans; biomass yield evaluations; wood quality assessments; nutrient requirement research; and genetic characterization investigations.

RESULTS

The results of these investigations follow.

Selections

Eight native North American species were selected for study. These include: *S. eriocephala, S. exigua, S. lucida, S. petiolaris, S. pellita, S. bebbiana, S. discolor,* and *S. amygdaloides*.

Most selections were made in south-central Ontario.

Selections were mainly based on sex, flowering ability, and freedom from disease, as the ability to produce biomass in energy plantations, could not be properly assessed on these shrubby willows.

Hybridization

Mating Design
The mating design for the hybridization work consisted of: 3 females x 3 males per species, each crossed within species and with every other species in the study for a total of 9 crosses per combination (Mosseler 1987). This design was implemented in order to assess the combining ability of the parents.

Compatibility
Studies were undertaken to establish possible reasons for fertility barriers in species combinations. Pollen germination and pollen tube development on the stigma were analyzed by fluorescence microscopy. Pollen tube growth inhibition was established as a principal reason for incompatibility. A Ph.D. study entitled "Interspecific hybridization and reproductive barriers between some North American willow species" by A.J. Mosseler (1987), was completed based on this work.

Family Testing

Family trials were established in order to evaluate growth performance, flowering phenology, sex ratios, fertility and morphological characteristics of *Salix* hybrids. Large within - and between - family variation was observed in these trials (Mosseler 1987).

Clonal Screening Trials

Four clonal screening trials were established to select the most promising individuals and to provide information on genetic by environmental interaction based on biomass production, growth habit, disease resistance and frost hardiness. There are approximately 300 clones per site, replicated in completely randomized block designs. Some clonal selections exhibit superior growth and some exhibit inferior growth over all testing sites. Other clones vary in growth between test sites. Clonal evaluations will continue on these sites.

The locations of the four Clonal Screening Trials are as follows: Maple, Ontario (OTIFBI); Kemptville, Ontario (OMNR); Petawawa, Ontario (PNFI); and Syracuse, New York (SUNY).

Advanced Breeding

Further breeding work was performed in order to produce more inter- and intraspecific hybrids of the most promising families. Crosses were made between the best *S. eriocephala* parent trees and hybrid combinations.

Backcrosses were also attempted in order to breed for specific desirable traits. For example, *S. eriocephala x S. exigua* hybrids were crossed with *S. eriocephala* and *S. exigua*. Backcrossing to the *S. exigua* parentage may incorporate the root suckering ability of *S. exigua* while backcrossing to *S. eriocephala* may improve form, disease resistance, and maintain good

biomass producing abilities.

Highly productive European clones of *S. viminalis* were crossed with the highest yielding North American species *S. eriocephala*, in order to further increase growth potential in the hybrids.

Crosses were also made in order to produce species sublines with high or low coppice numbers, and to determine the heritability of this trait.

Variation in Biomass Production and Quality

An evaluation of biomass production indicated that *Salix eriocephala* produced the highest yields averaging 1 kilogram per plant after one year of coppice growth, and had the lowest moisture content and highest specific gravity of the species studied (Mosseler *et al.* 1988). Yields of between 15 to 20 oven dry tonnes per hectare per year were found from unselected material at 1m x 1m spacing, harvested on 2-3 year rotations.

Significant variation in plant biomass, moisture content and specific gravity was due to species. Large within- family variation in the species studied suggested that the above traits could be substantially improved through clonal selection (Mosseler *et al.* 1988).

	Biomass production (kg)		
	Mean ± SE	Range	CV*
Salix eriocephala			
Seedlings	1.36±0.05	0.40-3.26	38.6
Coppices	0.98±0.04	0.06-2.43	41.4
Salix exigua			
Seedlings	0.65±0.03	0.13-1.60	46.6
Coppices	0.19±0.01	0.04-0.63	59.1
Salix lucida			
Seedlings	0.50±0.02	0.13-1.28	45.3
Coppices	0.23±0.01	0.01-0.66	55.4
Salix amygdaloides			
Seedlings	0.26±0.02	0.01-0.83	55.1
Coppices	0.12±0.01	0.01-0.50	68.1

* Coefficient of variation.

Table 1. Ovendry biomass production for 2.5-year-old seedlings and 1-year-old coppices of *S. amygdaloides*, *S. eriocephala*, *S. exigua* and *S. lucida*.

	Mean ± SE	Range	CV*
Salix eriocephala			
% moisture content	91.6±0.60	80.3-113.1	7.2
Specific gravity	0.457±0.002	0.404-0.538	5.5
Salix exigua			
% moisture content	100.1±0.73	84.3-127.2	8.0
Specific gravity	0.430±0.002	0.385-0.465	4.5
Salix lucida			
% moisture content	106.3±0.98	88.6-148.2	9.9
Specific gravity	0.394±0.002	0.293-0.443	5.1
Salix amygdaloides			
% moisture content	106.5±0.80	89.8-138.1	8.1
Specific gravity	0.421±0.002	0.367-0.464	4.7

* Coefficient of variation

Table 2. Percent moisture content and specific gravity of 1-year-old coppice shoots of *S. amygdaloides*, *S. eriocephala*, *S. exigua* and *S. lucida*.

Wood Quality Assessments

Wood quality determinations were studied to determine the variation within and among three species of willow (*S. eriocephala*, *S. exigua* and *S. lucida*) in amounts of extractives, hollocellulose, alphacellulose and hemicellulose. This information is essential if selection and breeding programmes are to include biomass quality traits as goals for improvement.

The results indicated that *S. eriocephala* exhibits the most favourable characteristics for biochemical conversion (Kenney 1989). *S. exigua*, while less productive, would provide similar feedstock qualities, provided bark to wood ratios were the same.

The greatest opportunities appear to exist for the modification of chemical traits in the bark. If one considers the dramatic differences that exist between the chemical characteristics of the wood and the bark, and the large amounts of bark that will be found in willow feedstocks grown on rotations of two to three years, it seems likely that some of the most dramatic gains in feedstock quality may be achieved through breeding for bark content (Kenney 1989).

Figures 1 and 2 indicate comparisons of the percent of total extractives and alphacellulose in wood and in bark. Species comparisons which do not exhibit significant differences as determined by a Duncan's Multiple Range Test, share a common letter below their name on the X-axis.

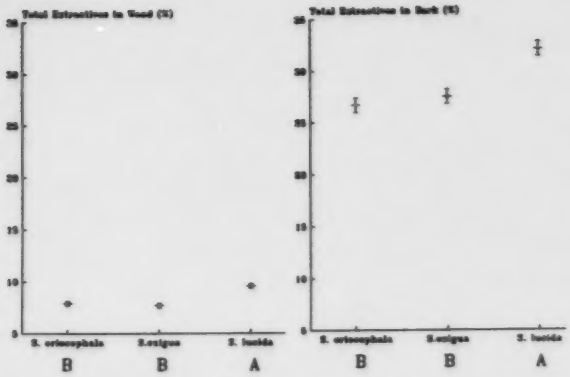

Figure 1 Means and standard errors (n=30) for the total extractive content in the wood and bark of three species of willow.

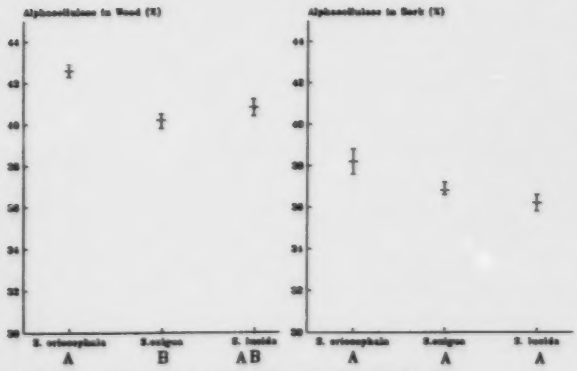

Figure 2 Means and standard errors (n=30) for the alphacellulose content in the wood and bark of three species of willow.

NUTRIENT REQUIREMENTS

Nutrient requirement experimentation, on willows grown in pots, demonstrated that spectacular results in biomass production could be obtained by fertilizing soils poor in nutrients. Applications of 125 kg/hectare of nitrogen in a balanced fertilizer regime resulted in an increase in biomass production by 255-484 percent over the control (Simon 1988). *S. eriocephala* produced 85-95 percent more biomass at 125 kg/hectare nitrogen than *S. lucida* and *S. exigua* respectively. Large clonal differences were observed within each species.

A second set of trials with Municipal and industrial (Dupont) sludge gave positive results. Plants treated with municipal sludge with liming treatments showed significantly better growth than those treated with chemical fertilizer or Dupont sludge (Simon 1988).

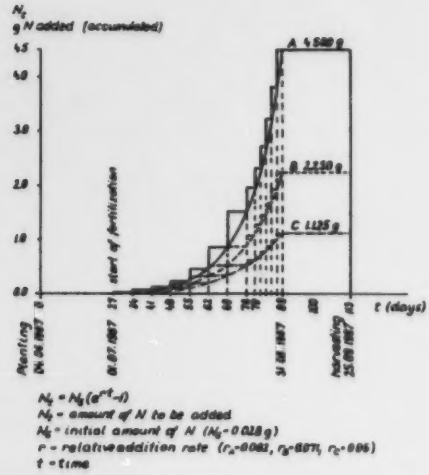

Figure 3. Exponentially increasing nitrogen addition in the chemical fertilization treatments.

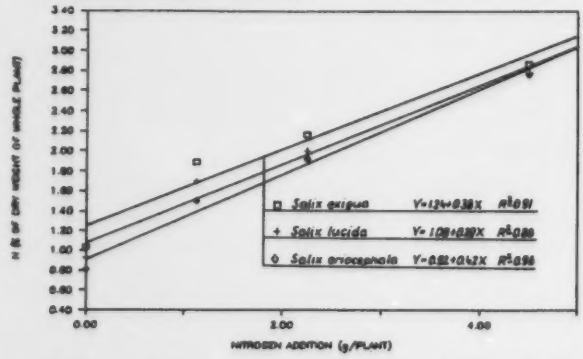

Figure 4. Nitrogen status (N%) of *Salix* plants at different levels of fertilization and associated regression for species.

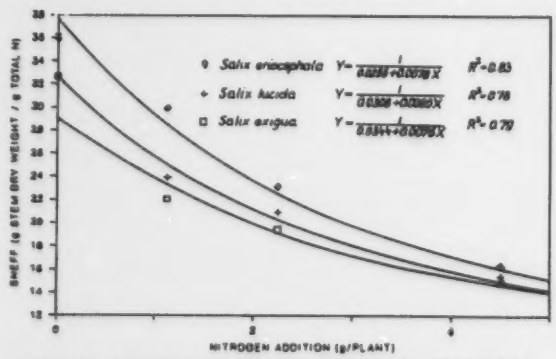

Figure 5. Stem nitrogen efficiency (SNEFF) of *Salix* plants at different levels of fertilization and associated regression for species.

Genetic Characterization Investigations

The genetic characterization of willows, in this breeding programme, has just started. Two Ph.D. theses proposals form the basis for this work. The proposals are entitled: "Dynamics of isozyme electrophoretic spectra in two *Salix* species and their implementation in willow breeding research" (Aravanopoulos 1989) and "Phylogenic relationships of willow species based on allozyme variation and chloroplast DNA diversity" (Chong 1989).

The first study, using enzyme electrophoresis, will examine inheritance and linkage relationships of *S. eriocephala* and *S. exigua* and their interspecific hybrids.

The second study will employ restriction fragment analysis and enzyme electrophoresis to elucidate evolution and species relationships of twelve species of North American willow, representing six sections and two subgenera.

DISCUSSION

Compatible hybrids and parent trees with good combining ability were identified in these studies. *S. eriocephala* is a very promising species with regard to growth and biomass qualities. Several species combinations may show promise for combining desired traits such as for root suckering or resprouting ability and disease resistance.

Average yields of better families indicated that 15 to 20 oven dry tonnes per hectare per year could be expected. Clonal selections from these families have a significantly higher yield potential.

Large variation was detected in characteristics for biochemical conversion. The greatest opportunities for improving feedstock quality could be achieved through breeding for bark content.

Spectacular improvements in biomass production were obtained by fertilizing soils poor in nutrients. Species and clonal variation in nutrient uptake efficiency indicate that clones could be selected which accumulate more biomass with less nutrient uptake.

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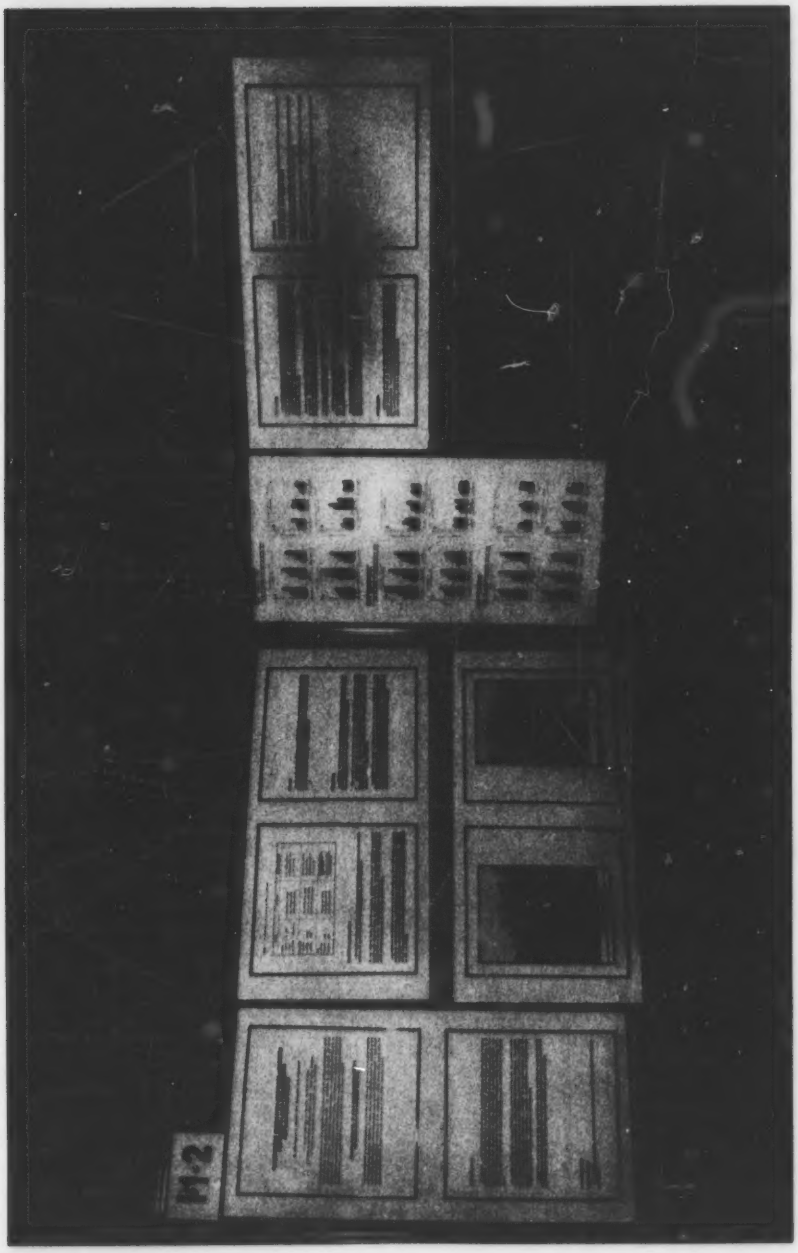
H-2

POTENTIEL DE CROISSANCE D'ESPÈCES LIGNEUSES DESTINÉES À LA CULTURE INTENSIVE PAR COURTES ROTATIONS

M. Labrecque[1], C. Richer[2], M.F. Beaudoin[1] et S. Popovich[3]

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La croissance annuelle et le développement de plusieurs espèces d'arbres et d'arbustes ont été suivis pendant quelques saisons consécutives. Les analyses de ces résultats ont permis d'identifier, parmi celles-ci, une dizaine d'essences indigènes et horticoles dont la croissance, en phase juvénile, s'est révélée particulièrement active. Considérant leur rusticité, leur résistance à la maladie et la productivité de leurs rejets après recepage, les espèces considérées représentent manifestement, un grand intérêt pour la culture intensive par courtes rotations.

The annual growth and developpement of a number of species of trees and shrubs were followed over consecutive seasons. Analyses of these results have identied about ten indigenous and horticultural species among those whose particularly active in the juvenile phase. In view of their hardiness, their resistance to disease and the productivity of their shoots after rejuvenation, the species considered are clearly of great interest for short-rotation intensive culture.

INTRODUCTION

Depuis plus de deux décennies, de nombreux chercheurs de pays différents ont commencé à s'intéresser à la possibilité d'utiliser le matériel forestier comme énergie renouvelable en le transformant thermodynamiquement ou biochimiquement en alcool ou autres combustibles. La crise du pétrole des années 70 aidant, beaucoup d'études ont été orientées dans le but de mettre au point des façons rapides, mais surtout économiques de produire la biomasse végétale (Christersson 1986; Ranney et al. 1987). De là sont nées les pratiques de culture intensive par courtes rotations (Heilman et Peabody 1981). Elles consistent à cultiver des arbres ou des arbustes, reconnus pour leur rapidité de croissance, en maintenant une haute densité de tiges à l'hectare et en recherchant une productivité maximum. De façon cyclique, les tiges sont recepées suivant des rotations d'une à sept années.

Au Jardin botanique de la Ville de Montréal, nos intérêts horticoles nous ont conduits à traiter et étudier des quantités d'essences et de variétés différentes d'arbres et d'arbustes. Plus récemment, nous avons entrepris de collaborer avec des chercheurs en horticulture d'Agriculture Canada afin d'élaborer un projet de recherche visant à évaluer le potentiel horticole d'un grand nombre de végétaux ligneux. Appelé, Réseau d'essais des plantes ligneuses ornementales, le projet a été mis sur pied en 1984 et a permis d'étudier le potentiel de croissance et la rusticité (à l'intérieur de trois différentes zones climatiques du Québec) de plus de 200 espèces et variétés d'arbres et d'arbustes.

Bien que cette étude ait surtout été orientée en fonction d'objectifs essentiellement ornementaux, plusieurs des espèces et variétés étudiées ont attiré l'attention par leur grande capacité de croissance en phase juvénile. Certaines présenteraient ainsi un attrait intéressant pour un projet où la considération première serait la production rapide de biomasse végétale.

Dans cette étude, nous avons analysé plus en détails, le comportement de quelques espèces qui ont manifesté un rythme de croissance particulièrement important durant les premières années de leur développement. Des arbustes appartenant à trois genres différents (Lonicera, Physocarpus et Salix) ont été étudiés.

L'objectif de ce travail est d'analyser les taux de croissance des espèces considérées, dans le but de vérifier si celles-ci pourraient être utilisées en culture intensive par courtes rotations pour des fins de production de biomasse.

MÉTHODOLOGIE

Taxons étudiés

La liste des taxons étudiés, leur provenance de même que leur mode de production figurent au Tableau 1.

Conditions expérimentales

Les travaux se sont déroulés à la ferme expérimentale d'Agriculture Canada de Ste-Clotilde, située à une quarantaine de km au sud de Montréal

(73°41'0-45°09'N). Le site de culture avait un sol bien drainé du type loam-sablonneux et le pH variait entre 6.0 et 6.5. Un labour profond (au moins 30 cm) a été pratiqué à l'automne précédent la plantation.

Les plants, enracinés en godets, ont été mis en terre en mai 1984, en respectant un protocole expérimental utilisé par toutes les stations du Réseau. Le bloc expérimental a été divisé en parcelles de 4 m par 2 m espacés les unes des autres de 2 m centre à centre. Chacune contenait 7 plants espacés de 50 cm et était répétée trois fois.

Tableau 1. [illegible]

[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

Les plants ont été irrigués en fonction de l'humidité ambiante et de manière à éviter tout stress hydrique. Un binage mécanique, entre les rangées et, manuel sur le rang, a été effectué pour contrôler les mauvaises herbes. L'année de la plantation un apport en fertilisant (54 g de 34-0-0 et 39 g de 0-15-30 par parcelle) a été fait à la mi-juin. Au cours des années subséquentes des amendements comparables ont été appliqués en mai, juin et juillet.

Mesures

À la fin de chacune des saisons de croissance, la hauteur (correspondant à la hauteur moyenne de trois ou quatre tiges principales) et la largeur (calculée au niveau le plus large) ont été mesurées sur 21 plants distribués dans trois parcelles. De la même manière, l'accroissement annuel de la hauteur et de la largeur a aussi été compilé.

RÉSULTATS

Les Figures 1, 2 et 3 présentent les histogrammes de croissance des différents taxons étudiés. Pour chaque genre, les valeurs de hauteur et de largeur mesurées en fin de saison, de même que les accroissements annuels en hauteur et en largeur ont été représentés.

Les espèces étudiées ayant tous un port arbustif, il est évident que leur croissance en hauteur atteint rapidement un plateau après trois ou quatre saisons de végétation (Figures 1A, 2A et 3A). Il demeure cependant, que plusieurs d'entre elles parviennent à dépasser les deux mètres de hauteur après seulement deux ou trois années. Les taux de croissance annuelle du Physocarpus opulifolius et du Salix eleagnos peuvent, par exemple, être supérieurs à un mètre (Figures 2B et 3B).

Figure 1. Croissance de Lonicera

A. Hauteur en fin de saison. B. Accroissement annuel en hauteur. C. Largeur en fin de saison. D. Accroissement annuel en largeur.

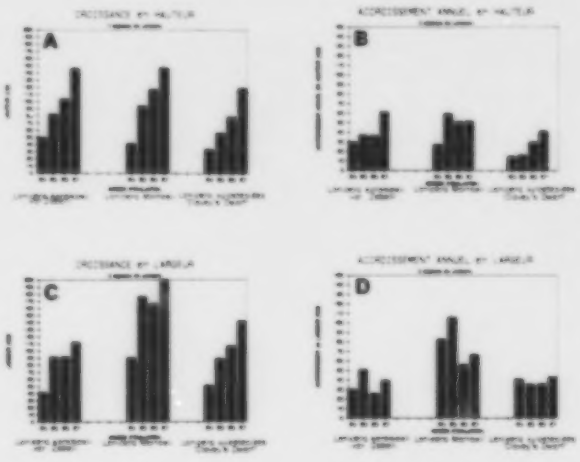


Figure 2. Croissance de Physocarpus

A. Hauteur en fin de saison. B. Accroissement annuel en hauteur. C. Largeur en fin de saison. D. Accroissement annuel en largeur.

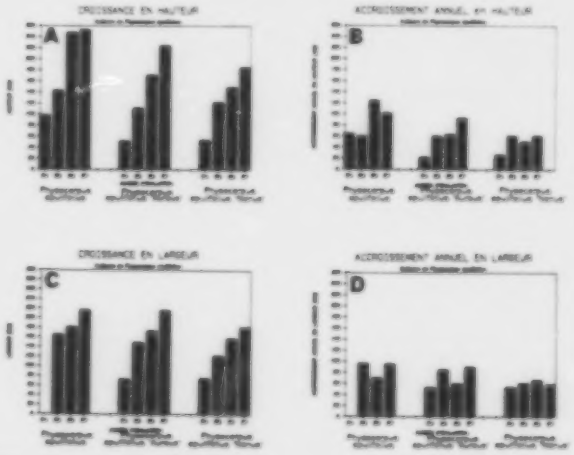
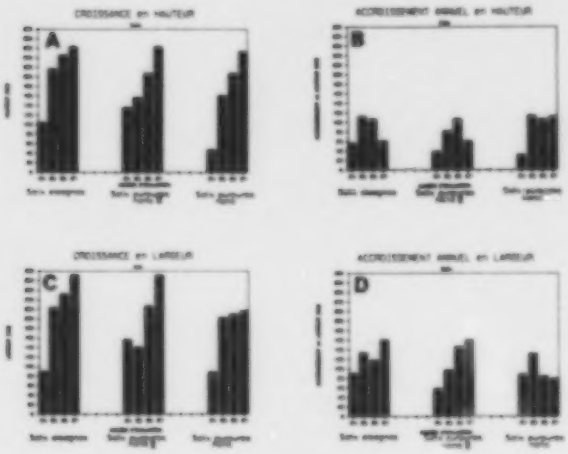


Figure 3. Croissance de Salix

A. Hauteur en fin de saison. B. Accroissement annuel en hauteur. C. Largeur en fin de saison. D. Accroissement annuel en largeur.



L'accroissement en largeur de certains des taxons est tout aussi remarquable. Les deux espèces de Salix, en particulier, ont atteint près de trois mètres de largeur après trois étés (Figure 3C) avec un rhythme annuel d'élargissement variant entre 1,3 m et 1,5 m. Notons que les plants de Salix purpurea 'Nana' qui ont été produits à partir de boutures récoltées en 1983 et cultivés en godets pendant seulement une année, ont performé de façon comparable à ceux qui avaient été cultivés pendant deux ans en pépinière. Leur croissance ne paraît qu'avoir été affectuée que pour le premier été suivant leur plantation (Fig. 2A, B, C, D). Le Lonicera morrowii a également manifesté un rythme annuel d'élargissement assez important, qui a atteint 80 cm la première année et plus d'un mètre l'année suivante (Figure 1D).

DISCUSSION

Les données exprimées sur les histogrammes des Figures 1,2 et 3 montrent que les espèces ont, en dépit du fait que leur croissance en hauteur plafonne après trois ou quatre ans, des taux annuels d'accroissement très appréciables. Certaines sont capables de produire des pousses annuelles de plus d'un mètre de long. Considérant l'élargissement et l'augmentation totale du volume des individus, la productivité annuelle représente certainement un intérêt pour les fins de production de biomasse.

Par ailleurs, les espèces mentionnées sont également intéressantes par leurs façons de réagir au recepage. Après fauchage, elles sont, en effet, réputées pour la forte productivité de leurs rejets. Les saules, et en particulier le Salix purpurea 'Nana', a démontré, lors d'autres expériences, une productivité accrue lorsqu'il était rabattu à chaque année.

Le recepage, pratiqué de façon régulière et répétitive, constituerait ainsi une façon d'augmenter la productivité des saules et probablement aussi celles de l'ensemble des espèces étudiées.

Ainsi, si l'on songeait à cultiver ces espèces selon les techniques de culture intensive par courtes rotations, il faudrait prévoir des cycles de fauchage assez rapprochés. Les recepages devraient alors être effectués chaque année ou à chaque deux ans, et le premier fauchage pourrait être réalisé après seulement deux ou trois années.

Les espèces étudiées sont également beaucoup moins sensibles aux maladies que les peupliers, qui pourtant sont très utilisés en culture intensive par courtes rotations (Zsuffa et al. 1977). Ces derniers vont fréquemment développer des maladies fongiques après le recepage, alors que les Salix, les Physocarpus et les Lonicera réagissent beaucoup mieux à cette pratique. Par contre certaines des espèces que nous avons étudiées, notamment le Lonicera xylosteoides 'Clavey's Dwarf', a manifesté des problèmes de gel lorsque la couverture de neigeuse restait trop faible en hiver. Pour cette raison les espèces plus sensibles au froid gagneraient à être rabattues à chaque fin de saison.

CONCLUSION

L'analyse sommaire des taux de croissance d'espèces arbustives, connues surtout pour leur potentiel horticole, montre que celles-ci pourraient également être exploitées pour leur grande productivité annuelle. Puisqu'elles réagissent bien aux fauchages répétés et qu'elles résistent bien aux infections et à la maladie, elles regroupent d'excellentes qualités pour être cultivées de façon intensive pour des fins de production de biomasse.

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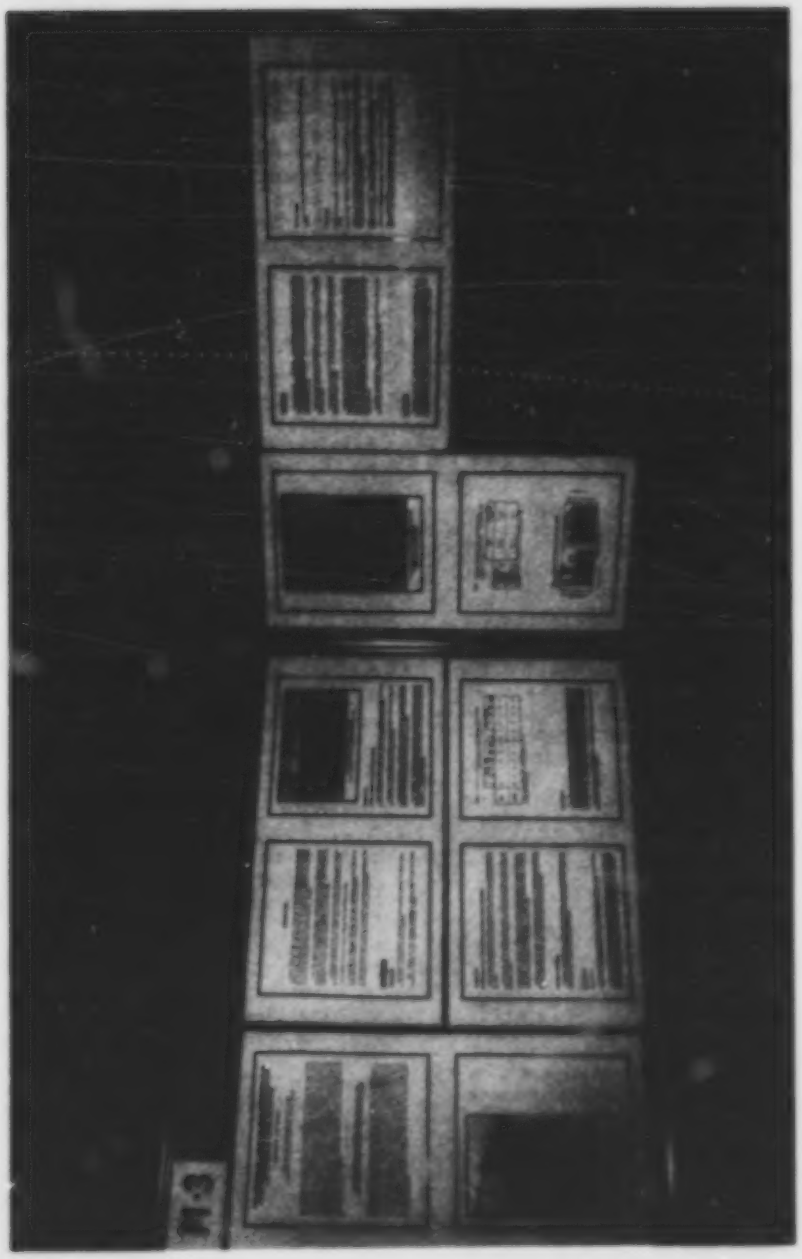

AMÉLIORATION DE LA RAPIDITÉ DE LA CROISSANCE ET DE LA QUALITÉ DES PLANTS D'ESSENCES FEUILLUES PAR L'UTILISATION DU TUNNEL DE CULTURE

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Des techniques de production sous tunnel de plants d'essences feuillues ont été expérimentées afin d'améliorer la rapidité de croissance et de favoriser le développement de plants sains et vigoureux. Les taux de croissance et les caractéristiques morphologiques de plants cultivés durant tout l'été sous tunnel et, parallèlement, au champ de la pépinière ont été comparés. Par la suite, des plantations expérimentales ont été réalisées afin de comparer la survie de plants d'un an, produits sous tunnel et de plants de deux ans, produits au champ. Le tunnel de culture avantage grandement la croissance des plants. Ni leur proportion, ni leur équilibre ne paraissent affectés par ce mode de production. De même la survie des plants 1+0 produits sous tunnel s'est révélée nettement supérieure à celles des plants 2+0 produits au champ. Le tunnel de culture serait un excellent moyen d'accélérer la rapidité de développement des plants tout en garantissant de meilleurs succès après la plantation.

Techniques of producing hardwood seedlings under tunnel were tested in an attempt to improve growth speed and promote the developpement of healthy, vigourous plants. The growth rates and morphological characteristics of seedlings cultivated throughout the summer under tunnel, on the one hand, and in the nursery field, on the other, were compared. Experimental plantings were subsequently made in order to compare the survival of one-year old seedlings produced under tunnel and two-year old seedlings produced in the field. The tunnel is of great benefit to the growth of seedlings. Neither their proportions nor their balance appear to be affected by this mode of production. Likewise, the survival of the 1+0 seedlings produced under tunnel proved clearly superior to that of the 2+0 seedlings produced in the field. The tunnel would be an excellent mean of accelerating the developpement of seedlings, while at the same time guaranteeing better success following planting.

INTRODUCTION

De façon conventionnelle, les plants d'essences feuillues destinés au reboisement du sud du Québec et de l'Ontario ont longtemps été produits au champ de la pépinière par des méthodes de cultures plutôt empiriques (Stroempl 1985). Plus récemment et, compte tenu de l'importance qu'ont prit les programmes gouvernementaux de reboisement, les pépiniéristes ont commencé à rechercher des méthodes de production beaucoup plus efficaces.

Dans cette optique, nous avons entrepris, depuis quelques années, d'explorer de nouvelles techniques de culture susceptibles d'accélérer la croissance et la qualité des plants d'essences feuillues produits pour le reboisement (Labrecque et Popovich 1987; 1988). C'est ainsi que l'utilisation du tunnel à couverture de polyéthylène a été expérimentée. Les avantages de celui-ci sont bien connus des horticulteurs surtout pour ses applications en culture hâtive de plantes annuelles, de fruits et de légumes (Hall et Baumer 1972; Tinus et McDonald 1979).

La technique que nous avons mise au point consiste à cultiver les plants en pleine terre tout en les abritant, durant toute la saison estivale, sous la couverture de polyéthylène du tunnel.

Par ce travail, nous avons voulu vérifier les deux hypothèses suivantes:

a) La méthode de culture sous tunnel que nous avons développée permet-elle d'améliorer de façon significative la rapidité de croissance des plants d'essences feuillues?

b) Dans l'affirmative, peut-on croire qu'une accélération de la croissance et du développement des plants puisse nuire à leur chance de survie et de reprise après la plantation?

MÉTHODOLOGIE

Généralités

Les travaux ont été réalisés à la pépinière du Jardin botanique localisée à Terrebonne (45° 41'N-74°40'O), à quelques km au nord de Montréal.

Cette pépinière est située sur une ancienne terre agricole qui a acquis sa vocation actuelle depuis 1966. Le sol, sablo-limoneux (Clayton et al. 1977), est bien drainé et son pH varie autour de 6.0-6.5.

Deux espèces de chêne, Quercus macrocarpa et Quercus rubra ont servi de matériel d'études pour réaliser les deux expériences décrites ci-dessus.

Expérience 1

Comparaison de la croissance des plants

La croissance de plants cultivés sous tunnel a été comparée à celle de plants qui ont été produits, parallèlement au champ, dans une parcelle située juste à côté de celui-ci.

Les semis de chaque espèce ont été faits à l'automne et répartis en six blocs différents selon une densité (après germination) d'environ 40 plants par m^2.

Les plants ont été cultivés sous des conditions d'éclairage naturel où la photopériode était de 16±2 heures. À l'intérieur du tunnel, il n'y a eu aucun éclairage d'appoint et la ventilation n'a été assurée que par l'ouverture de volets latéraux. La couverture de polyéthylène a été retirée à la fin du mois de septembre. Les mêmes soins d'irrigation et de contrôle des mauvaises herbes (fait manuellement) ont été apportés aux plants, qu'ils aient été cultivés dans les parcelles situées au champ ou sous tunnel.

En fin de saison, 18 semaines après la germination des semis, 30 échantillons de chacun des deux traitements (culture au champ et sous tunnel) ont été choisis aléatoirement et arrachés. Des mesures de hauteur, de diamètre au collet (mesuré à un cm au-dessus du sol) et de masses anhydres ont été prises et comparées.

Expérience 2

Comparaison de la survie et de la croissance après la plantation

Des plantations expérimentales ont été réalisées afin de comparer la survie et l'accroissement en hauteur de plants produits, soit sous tunnel (PST) en un an (1+0) , soit au champ (PAC) en deux ans (2+0). Notons qu'en raison des dimensions restreintes que les plants PAC peuvent atteindre après une saison, il aurait été impossible d'utiliser des plants (1+0) pour faire cette comparaison.

Pour chacune des deux espèces considérées, 120 plants d'un an PST et autant de plants de deux ans PAC, ont été choisis au hasard au printemps parmi un stock de plants arrachés à l'automne précédent (1986).

Une planteuse à disques a été utilisée pour réaliser la plantation qui a été réalisée au mois de mai 1987. Les plants ont été répartis en rangées (avec un espacement d'un mètre entre les plants et de deux mètres entre les rangées) en respectant un dispositif aléatoire de blocs complets. Chaque bloc a été répété six fois et contenait 20 plants. Le contrôle des mauvaises herbes s'est fait par rotoculture entre les rangées et manuellement entre les plants.

Avant la plantation, la hauteur et le diamètre au collet (pris à un cm au-dessus de la surface du sol) de 30 plants, sélectionnés au hasard, ont été mesurés. De même les pourcentages de survie ont été évalués à différents intervalles: deux, douze et dix-dept mois après la plantation.

Analyses statistiques

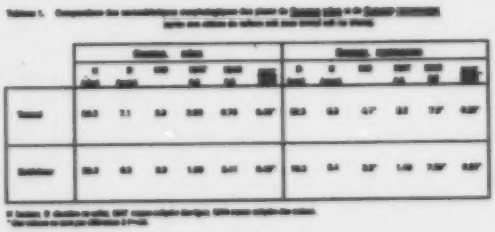
Toutes les valeurs discutées ont fait l'objet d'analyses de variance. Les pourcentages de survie ont subit une transformation angulaire (arc sinus, racine carrée) (Draper et Smith 1980) avant d'être traitée par des tests statistiques paramétriques.

RÉSULTATS

Expérience 1

Le mode de développement des plants des deux espèces de chêne étudiées est comparable et la culture sous tunnel a provoqué, pour toutes les deux, les mêmes conséquences sur leur croissance. Ainsi, lorsqu'ils sont cultivés sous tunnel, les plants manifestent souvent trois et même parfois quatre vagues d'allongement alors qu'ils développeront rarement plus de deux poussées de croissance lorsqu'ils sont produits au champ. Les valeurs de hauteur, de diamètre au collet et de masses anhydres qui figurent au Tableau 1 montrent d'ailleurs très bien la nette supériorité de la croissance des plants cultivés sous tunnel.

Cette augmentation de la croissance paraît se faire sans pour autant affecter l'équilibre morphologique des plants. Les plants PST ont tendance à être plus allongés, tel qu'en témoignent leur rapports hauteur/diamètre au collet (Tableau 1) mais leurs proportions, exprimées par le rapport des masses anhydres (tiges/racines), sont comparables à celles des plants PAC (Tableau 1).



Expérience 2

Au Tableau 2, sont présentées les caractéristiques morphologiques des plants qui ont été utilisées pour réaliser les plantations expérimentales. Les valeurs de hauteur et de diamètre au

Tableau 2. Valeurs moyennes des hauteurs et des diamètres au collet mesurées au moment de la plantation sur des plants de Quercus macrocarpa et de Quercus rubra produits soit sous tunnel, soit au champ.

	Hauteur (cm)	Diamètre au collet (mm)
Quercus macrocarpa		
Produits sous tunnel (1+0)	33.3 ± 7.2	6.8 ± 1.0
Produits au champ (2+0)	45.5 ± 19.4	10.1 ± 3.2
Quercus rubra		
Produits sous tunnel (1+0)	33.8 ± 11.9	6.4 ± 1.0
Produits au champ (2+0)	51.6 ± 15.8	10.3 ± 1.5

Pour une même espèce les valeurs moyennes des hauteurs et de diamètres au collet sont toutes significativement différentes à P=.05.

collet des plants de deux ans PAC sont significativement plus grandes que celles des plants PST en une saison. Cependant la Figure 1 montre que les taux de survie de ces derniers se sont révélés nettement supérieurs. Par exemple, les plants de Quercus rubra PST manifestaient 95.4% de survie deux mois après la plantation contre seulement 66.1% pour les plants PAC (Figure 1).

Cette forte différence de survie observée deux mois après la plantation ne s'est toutefois pas accrue dans les mois suivants. Les taux de survie des plants de Quercus macrocarpa, par exemple, sont demeurés inchangés même après que ces derniers aient subit les rigueurs de l'hiver (Figure 1). De la même façon, la Figure 1 montre que les différences entre les pourcentages de survie des plants de Quercus rubra sont devenues de moins en moins significatives 12 et 17 mois après la plantation.

DISCUSSION

Les résultats présentés au Tableau 1, montre de façon évidente, que la méthode de production sous tunnel que nous avons expérimentée est très efficace pour accélérer la croissance et le développement de plants d'essences feuillues. Après une saison de culture sous tunnel les deux espèces de chêne étudiées peuvent atteindre des dimensions qui permettent leur plantation dès le printemps qui suit.

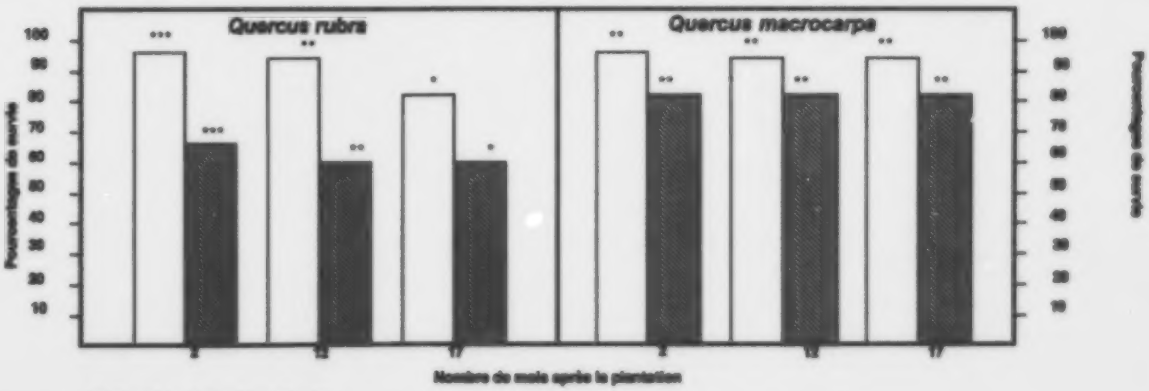
Dans la seconde expérience qui a été réalisée, nous avons justement voulu vérifier laquelle des deux méthodes (production au champ ou sous tunnel) permettait de meilleurs rendements après la plantation.

Plusieurs auteurs reconnaissent qu'en général les plants de plus fortes tailles sont avantagés après la plantation (Von Althen 1974; Webb et Von Althen 1978; Chavasse 1983). Aussi, considérant la supériorité des dimensions des plants PAC en deux ans (Tableau 2), nous avions cru que ceux-ci auraient connu de meilleures performances après la plantation. Or il s'est avéré que ce sont les plants PST en une saison qui ont présenté les pourcentages de survie les plus élevés (Figure 1).

La culture sous tunnel aurait-elle favorisée le développement de plants de meilleure qualité?

Il est certain que le fait de cultiver des plants, en les abritant sous une couverture de polyéthylène, permet de maintenir tout au cours de la production, des conditions très favorables à leur développement: des températures de l'air et du sol plus chaudes, un taux d'humidité plus élevé et une plus forte teneur en gaz carbonique (Hall et Besemer 1972; Tinus et McDonald 1979). De plus les plants se trouvent ainsi protégés des excès de la météo (gels tardifs, vents desséchants, fortes pluies ou verglas) souvent changeantes dans le sud du Québec. Mais il demeure plus probable que les différences que nous avons observées dans les taux de survie soient davantage liées à la morphologie même des plants. La Figure 1 démontre que les plants PAC sont touchés de façon importante par la mortalité dans les semaines qui suivaient la plantation, mais que par la suite, les pourcentages de survie demeuraient relativement stables jusqu'au dernier relevé fait 17 mois après la plantation.

Figure 1. Comparaison des pourcentages de survie après la plantation de plants produits, soit sous tunnel en un an (colonnes claires), soit au champ en deux ans (colonnes sombres).



*** P=.001 ; ** P=.01 ; * P=.05

Le choc de transplation subit par les plants de deux ans PAC aura été probablement beaucoup plus important que celui qu'ont eu à supporter les plants d'un an PST. Malgré les soins très méticuleux qui avaient été apportés lors de l'arrachage à l'automne 1986, il est en effet vraisemblable de penser que le traumatisme, causé aux racines des plants de deux ans, ait été beaucoup plus dommageable. Il est d'ailleurs reconnu que le fait de sectionner ou d'amputer trop sévèrement le système racinaire de plants de chêne rouge, engendrait de sérieux problèmes de mortalité (Beckjord et Cech 1980; Stonehas et Thoday 1985).

Ainsi, non seulement la culture sous tunnel accélère-t-elle la croissance des plants mais, en permettant de produire en une seule saison le matériel destiné à la plantation, elle favorise un enracinement moins profond des plants, notamment de ceux qui développent des pivots comme les chênes et les noyers. L'intensité du choc causé aux plants à l'arrachage se trouve réduit, il en résulte probablement une meilleure aptitude à reprendre et à survivre après la plantation.

Remerciements

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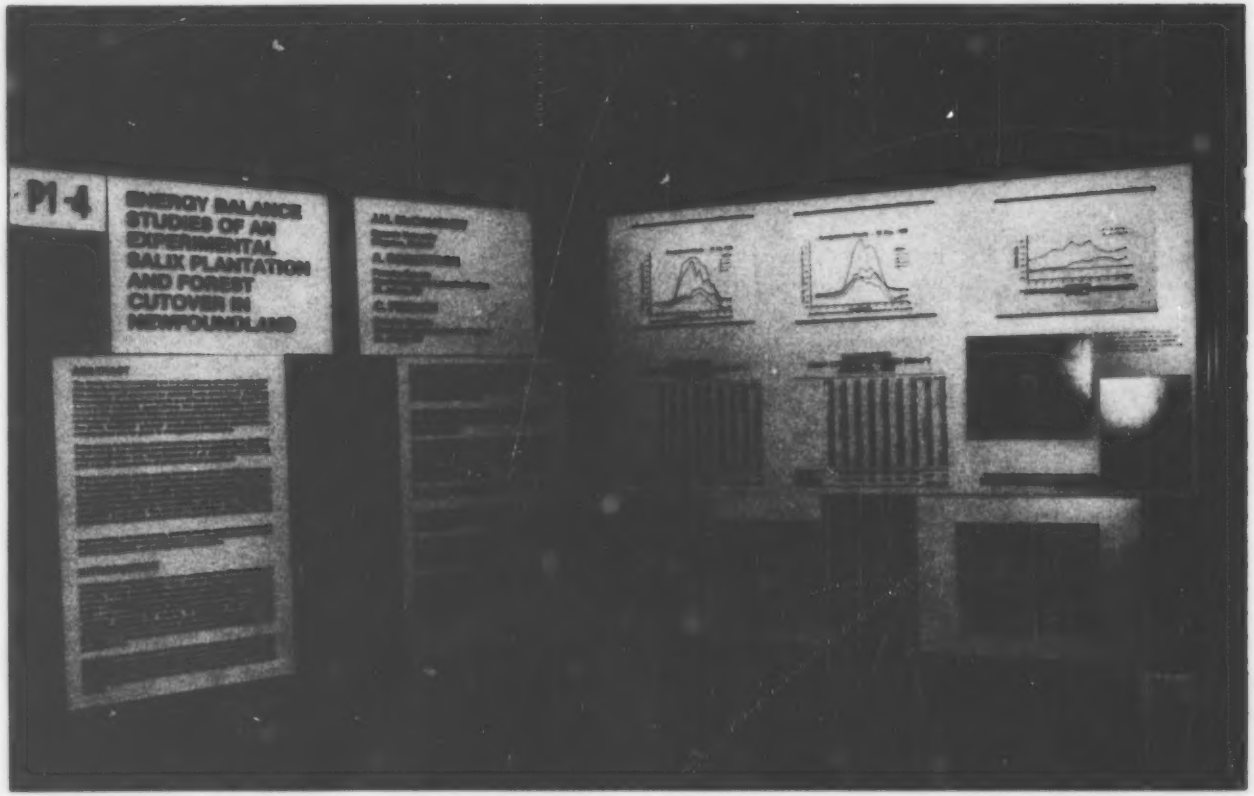
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ENERGY BALANCE STUDIES OF AN EXPERIMENTAL SALIX PLANTATION AND FOREST CUTOVER IN NEWFOUNDLAND

ENERGY BALANCE STUDIES OF AN EXPERIMENTAL SALIX PLANTATION AND FOREST CUTOVER IN NEWFOUNDLAND

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The forests of Newfoundland are in a climatically sensitive region such that disturbance by exploitation and forest fires can lead to site degradation, whereby vast areas can be rendered unto scrub forest. Restoring these regions to productive forests is a difficult undertaking. Even if the forest is not degraded, sensu stricto, the typical productivity of boreal forest in this region is far below what can be achieved through intensive silviculture. Regardless of silvicultural options, there is a need for prediction of the theoretical maximum productivity of specific sites before any consideration can be given to management investments.

Since energy is the basis of all life, it follows that assessing the partitioning of energy into various components such as sensible heat, soil heat, evapotranspiration, and, most important of all, storage in biomass, will give a better appreciation of potential forest production.

Results of a study on the energy balance and other climatic processes of an experimental energy plantation and a forest cutover in Newfoundland are summarized. The energy balance measuring system is based on the energy balance/Bowen ratio method using an automated unit consisting of a Reversing Temperature Difference Measurement System (RTDMS) and associated sensors for net radiation, soil heat flux, heat storage, precipitation, and wind. The unit has a datalogger that collects and processes the data and controls the frequency of the RTDMS. The unit is powered by a 12 volt battery and can also be remotely monitored and programmed through teleconnections. Supporting PC computer software solves the radiation and energy balance equations.

Les forêts terre-neuviennes sont situées dans une région sensible au climat, si bien que toute perturbation due à l'exploitation et aux feux de forêt peut entraîner une dégradation transformant de vastes étendues en forêt sèche basse. Il est ensuite difficile de restaurer ces régions pour les rendre de nouveau productive. Même si la forêt n'est pas dégradée au sens strict, la productivité typique de la forêt boréale dans cette région est loin de celle que l'on peut obtenir grâce à des pratiques de sylviculture intensive. Quelles que soient les options sylvicoles, il est nécessaire de prévoir la productivité théorique maximale de sites spécifiques avant d'envisager d'investier dans la gestion.

L'énergie étant la source de toute forme de vie, le fait d'évaluer la répartition de l'énergie dans ses différents éléments, à savoir la chaleur sensible, la chaleur du sol, l'évapotranspiration, et surtout, le stockage dans la biomasse, permettra de mieux déterminer la production potentielle de la forêt.

On résume les résultats d'une étude portant sur le bilan énergétique et sur les processus climatiques dans une plantation expérimentale et dans une zone coupée à blanc à Terre-Neuve. Le système de mesure du bilan énergétique est basé sur la méthode du rapport de Bowen/bilan énergétique que fait appel à une unité automatisée constituée d'un Système de Mesure des Différences de Température à Renversement (SMDTR), relié à des capteurs du rayonnement net, du flux thermique du sol, du stockage thermique, des précipitations, et du vent. L'unité est munie d'un consignateur de données qui recueille et traite les données et qui règle la fréquence du SMDTR. L'unité est alimentée avec une pile de 12 volts et peut également être contrôllée et programmée à distance grâce à des téléconnexions. Un programme de soutien pour ordinateur PC résout les équations décrivant le rayonnement et le bilan énergétique.

INTRODUCTION

Climatological studies provide a basic understanding of the radiation and energy balances of plantation sites, and are integral to matching clone and site. To this end, the Bowen ratio is the most widely used and acceptable method for measuring evaporation from vegetation, providing there is an adequate fetch. The system for measuring the Bowen ratio used in Newfoundland consists of a RTDMS (Reversing Temperature Difference Measurement System) using psychrometry and a vertical interchange apparatus for sensors (McCaughey 1988; McCaughey et al. 1987). In association with independent measurements of net radiation, soil and biomass heat storage, the energy balance of the surface is solved. An advanced field datalogger (Campbell Scientific Canada Corp., Models CR7 or 21X) is used to collect the data and to control the timing of the interchange of the psychrometers. Anemometers have also been installed at two levels to measure the wind profile (McCaughey and Robertson 1989).

In support of the field system, three computer analysis programs are available:
- RADBAL provides summaries of the radiation balance, including the reflection coefficient, the radiative surface temperature, taking into account the soil and air temperature and the site's zenith angle distribution;
- STORAG calculates the individual components of the heat storage of the canopy and soil that are used as input into the ENBAL program;
- ENBAL calculates the Bowen ratio and the terms of the energy balance. In calculating the Bowen ratio, the temperature differences are corrected for adiabatic temperature change. Also, a number of diagnostic variables are computed, including the equilibrium evapotranspiration, the Priestley-Taylor potential evaporation, the primary resistances of the Penman-Monteith model, the surface-atmosphere decoupling coefficient, and the Richardson number, obtained from measurements of the wind profile.

Each of the programs is command-driven and interactive, and can work with incomplete data sets if necessary.

In Newfoundland, the first RTDMS was installed at Glenwood in the summer of 1986 on a site stripped of vegetation for an experimental energy plantation; thus, initial measurements provided baseline information of the energy balance and radiation balance of bare soil. Planting of the 10-hectare site was completed in 1987, and the RTDMS was also deployed in the summers of 1987 and 1988, respectively. Future RTDMS and associated measurements will focus on the radiation and energy fluxes of a developing Salix plantation. Another RTDMS system was installed in a cutover at St. George's in western Newfoundland in 1988, the results of which are still being processed.

RESULTS

The full results of the energy balance studies over three summers would be too voluminous to summarize here. Therefore, the following is a brief summary of representative samples from the data.

Two representative sample days, July 27 and August 22, 1986, demonstrate the ability of the measurement system to handle short-term (hourly) data. The partitioning of the energy balance components of these two days (Figures 1 and 2) represent differences in volumetric soil moisture content in the top 10 cm of soil. For example, on July 27, the energy balance is typical for a day with a wet soil surface where the latent heat flux (evapotranspiration) exceeds the sensible heat flux. On this particular day, the volumetric soil moisture was 22%, and precipitation on the previous day had been 12 mm. Conversely, August 22 is typical of a day with a dry soil surface, with volumetric soil moisture at 16%, with no precipitation recorded over the previous eleven days.

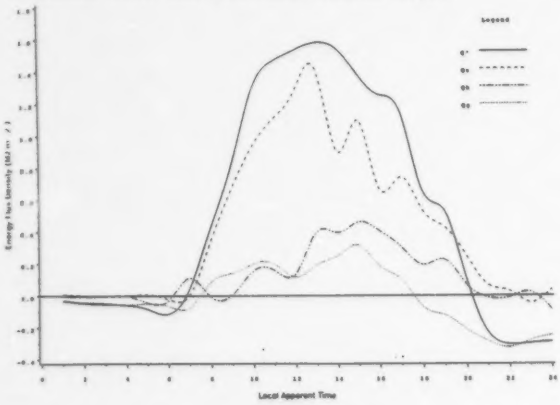

Figure 1. Energy balance components for July 27, 1986 at Salmon Pond, Newfoundland

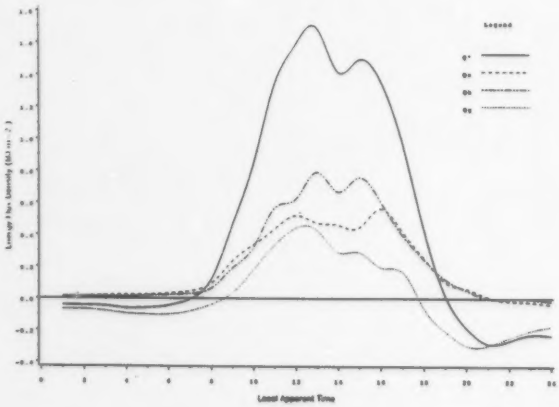

Figure 2. Energy balance components for Aug. 22, 1986 at Salmon Pond, Newfoundland

The daytime (when net radiation >0) hourly Bowen ratio patterns for these two days (Figure 3) illustrate that the energy partitioning is quite different. On July 27, the Bowen ratio is low and steady, indicating that most of the available energy was dissipated as evaporation, amounting to 84% of the daily total net radiation and 71% of the daytime total. Evaporation was in phase with the net radiation, reaching its peak at solar noon but continuing positive well into the night (Figure 1). Sensible heat flux amounted to 17-20% of the net radiation. In contrast, when soil moisture is limiting, sensible heat flux accounts for most of the energy usage (54% of net radiation on a daily basis and 45% on a daytime basis) and exceeds evaporation for most of the day (Figure 2). During the midday period, sensible heat becomes the dominant energy transfer mechanism from the surface as a response to the lack of moisture.

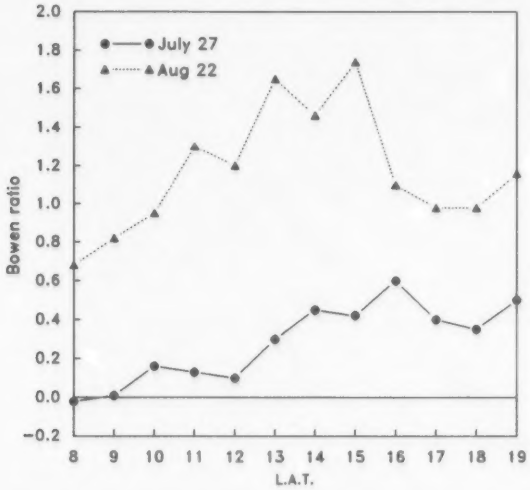

Figure 3. Hourly average Bowen ratios for July 27 and August 22, 1986 at Salmon Pond, Newfoundland

The low fluctuations of the Bowen ratio for August 27-30, 1987 (Figure 4) contrast with high fluctuations for the period August 20-25. The energy partitioning for each of these two periods is quite different, with the former period representing a time of adequate soil moisture, and the latter a drying-out phase. Towards sunrise and sunset, large fluctuations in the Bowen ratio are expected as a result of (i) the adjustment of net radiation between positive and negative values; (ii) the development of weak temperature and humidity gradients above the surface; and (iii) the increasing relative errors of measurement of the temperature differences. The Bowen ratio at 1730 h for August 20-25 (Figure 4) is an example of such a fluctuation. However, considering that there is little energy available for evaporation at these times, the impact on daily and daytime totals is negligible.

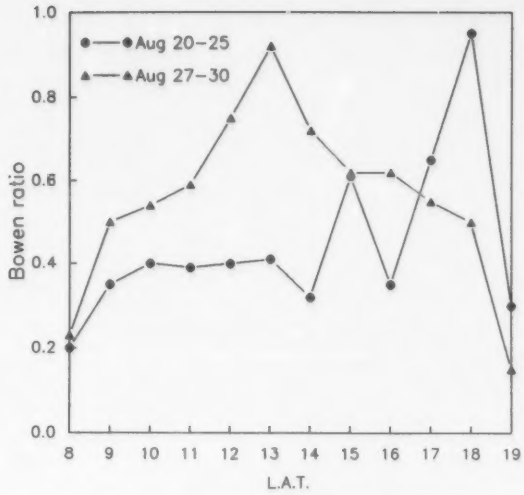

Figure 4. Average hourly Bowen ratios for August 20-25 and August 27-30, 1987 at Salmon Pond, Newfoundland

Figure 5 shows the relationship between daily totals of actual (Q_e) and equilibrium (EQ_e) evaporation over the measurement period June 28-August 25, 1986. The $Q_e = 1.26\ EQ_e$ line represents the potential evaporation determined by the Priestley-Taylor model, as well as the upper limit of the scatter of the data. The lower limit is at a slope of approximately 0.8. The 1:1 line represents equilibrium evaporation. Generally, evaporation proceeds between the equilibrium and potential rates, such that the data near the upper limit represent wet days or days immediately following rainfall when the soil is wet; whereas, the lower limit is represented by eight dry days when soil moisture was limited (French 1988). This supports the suggestion by Novak and Black (1983) that the Priestley-Taylor model can be used as an indicator of soil moisture, whereby α values >1.15 indicate wet soil, 1.0-1.15 indicate moderately dry soil, and <1.0 indicate dry soil conditions.

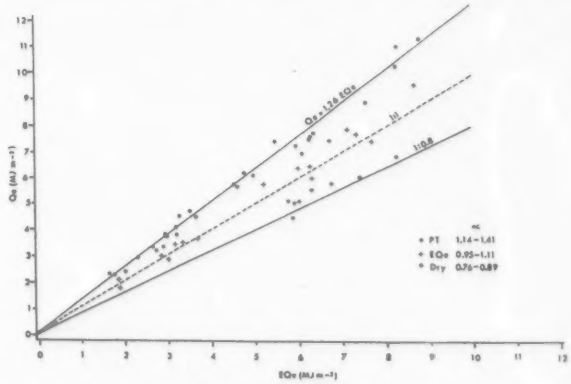

Figure 5. Daily totals of actual and equilibrium evaporation, June 28-August 25, 1986 at Salmon Pond, Newfoundland

CONCLUSIONS

The RTDMS designed for measuring the convective energy fluxes in plantations and forests is robust and requires a minimum of maintenance. For each of three summers the system operated more or less continuously for fifty days during the main growing season. The datalogger and supporting computer software simplify the data processing and analysis, and enhance the investigative aspects of the work.

The results obtained from the RTDMS and associated measurements for selected periods characterize the radiation and energy balances of a forest cutover in Newfoundland.

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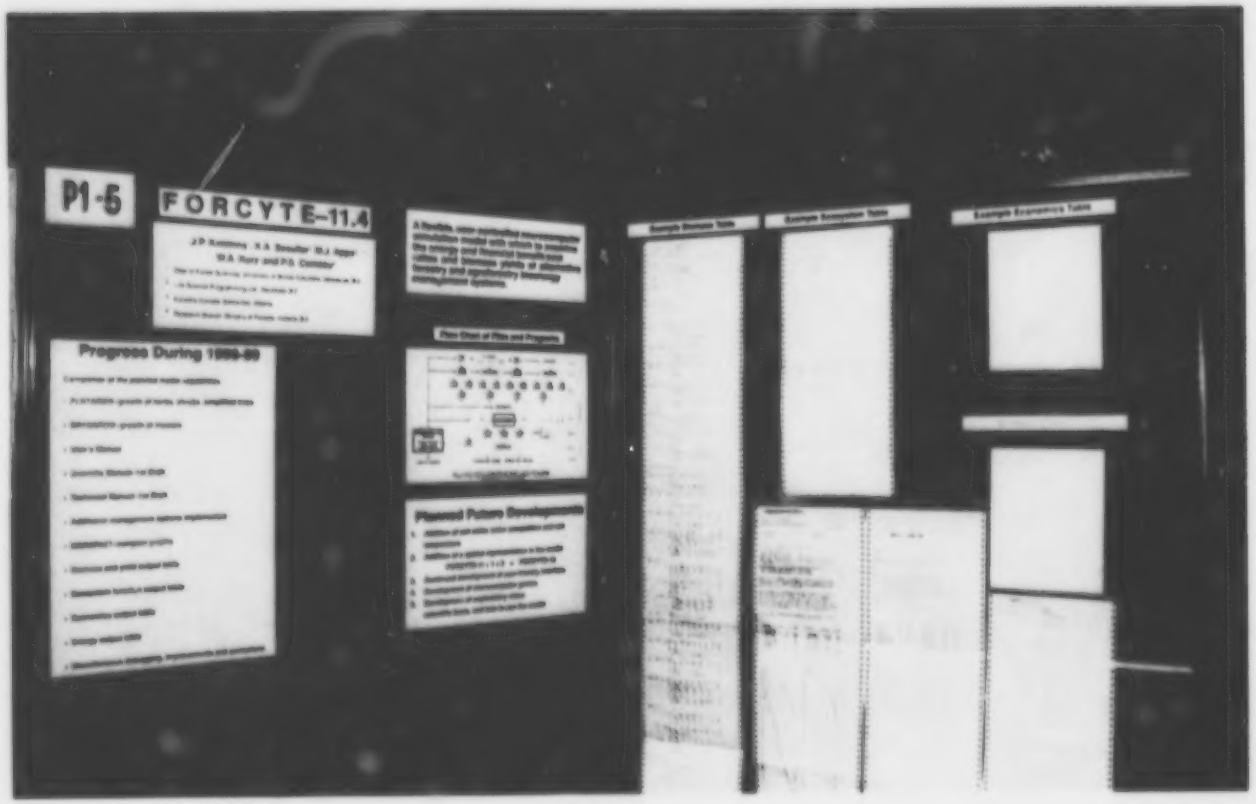
P1-5
FORCYTE-11.4
Progress During 1988-89
Planned Future Developments

FORCYTE-11: A FLEXIBLE, USER-CONTROLLED MICROCOMPUTER SIMULATION MODEL WITH WHICH TO EXAMINE BIOMASS YIELDS OF ALTERNATIVE FORESTRY OR AGROFORESTRY MANAGEMENT SYSTEMS

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The World Commission on Environment and Development has issued a challenge in its report "Our Common Future": to demonstrate that all future developments are consistent with a sustainable environment and sustainable renewable resources. In forestry, this requires projections over at least several rotations (a three-rotation minimum has been suggested by a IUFRO Working Group) concerning the sustainability of yield and site productivity under alternative management strategies. In the absence of empirical experience over such long time spans, interim estimates of sustainability can be obtained by calibrating and using models like FORCYTE-11.

The development of the FORCYTE series of ecosystem management models was a component of the ENFOR program of the Forestry Canada, which was initiated in response to the oil shortages of the mid 1970's. Initially a simple input-output model to examine soil fertility aspects of the sustainability of intensive biomass-for-energy projects, FORCYTE-11 has been developed to become an ecosystem management model with which to simulate the short and long- term effects of a wide variety of rotation-length management strategies on stand-level production, yield, yield sustainability, and economic and energy benefit/cost ratios. Although FORCYTE-11 cannot address questions that relate to climate change (the "greenhouse effect"), it can examine the effects of management on long-term site (i.e. soil) productivity.

INTRODUCTION: ORIGINS OF FORCYTE

The apparently inevitable doubling of world population from the present 5.2 billion to about 10 to 11 billion (Repetto 1987; World Resources Institute and International Institute for Environment and Development 1988), together with the increasingly serious deterioration of the global environment (e.g. Morrison 1984; Shands and Hoffman 1987), led the United Nations to establish the World Commission on Environment and Development. Their report, "Our Common Future" (World Commission on Environment and Development 1987), concluded that while the industrialized nations bear a grave burden of responsibility for current and past environmental deterioration, the greatest long-term threat to the environment comes from poverty in the populous developing countries. The Commission concluded that the long-term survival of the human species on earth depends on the elimination of this poverty, and that this will require the sustainable development of the World's resources. This in turn implies the need for planning tools with which to establish the sustainability of all future resource developments.

The oil crisis of the mid 1970's sent a shock wave through the industrialized nations who vowed to undertake the necessary steps to reduce our dependence on fossil fuels. The International Energy Agency was created, with subprograms to examine the feasibility and sustainability of biomass-for-energy production systems. A parallel activity in Canada, the ENFOR (Energy-from-the-forest) program of the Forestry Canada (funded by Energy, Mines and Resources) also investigated the sustainability of bioenergy production systems in forestry. A small project in this program was to review the soil fertility implications of whole-tree harvesting bioenergy tree plantations on short rotations, and to prepare a simple nutrient input/output model by which to establish the site nutrient budget for such harvesting systems. This was to become the basis for speculations about the sustainability of yield in energy plantations. Initial work on this input/output model revealed that such a simplistic model would tend to give simplistic answers. The significant questions could only be answered in a significant and believable manner by a much more complex approach. It was therefore concluded that a mechanistic,ecosystem-level computer simulation model capable of simulating all the major bioenergy plantation management options was needed.

This conclusion was the genesis of the FORCYTE (the FORest nutrient Cycling and Yield Trend Evaluator) series of models. Credit for the genesis of the model must go to the

pioneering work of the late Dr. Peter Rennie (Rennie 1955, 1957) and Dr. A. (Jock) Carlisle, whose tireless insistence on the need for such an evaluation tool made the development of FORCYTE possible.

A BRIEF HISTORY OF MODEL DEVELOPMENT

FORCYTE developed out of a 1977/78 ENFOR contract.

FORCYTE-1 was a simple historical bioassay (see Kimmins 1985, 1986, 1988) mathematical model of forest growth including herbs, shrubs and trees, with simulated nutrient cycling, but no feedback between nutrient availability and forest growth. This initial model was a foundation from which a useful model could be developed, but it could not be used to address the critical questions. Over the subsequent five years, the model was developed to FORCYTE-10 (Kimmins and Scoullar 1983). The various intermediate versions of the model (FORCYTE-2 to FORCYTE-9) represented significant stages in the development of this benchmark version: addition of nutrient feedback, of a simulation of site quality change, of various management activities, of tabular as well as graphical output, of energy analysis, and of economic analysis. FORCYTE-10 has been field tested in British-Columbia (Feller et al. 1983), Newfoundland (Meades 1987, Moore and Meades 1987), Oregon (Sachs and Sollins 1986), Finland (Kellomaki and Seppala 1987), Alaska (Yarie 1986), and the southern pine region of the US (Fox et al. 1984).

Useful as a teaching and research tool, and suitable for use as a qualitative decision support tool in some aspects of bioenergy plantation management or conventional forest management, FORCYTE-10 proved to have several shortcomings that limit its use as a more quantitative management decision support tool. Consequently, a further five years were supported by Forestry Canda (ENFOR) to develop its successor, FORCYTE-11. Whereas the series FORCYTE-1 to FORCYTE-10 constituted the definable stages in development of the benchmark FORCYTE-10, development of FORCYTE-11 involved a major restructuring of the model. This was necessary to overcome those unacceptable limitations of FORCYTE-10 that were the result of the modelling approach of that model. FORCYTE-11 is a modelling framework rather than an individual model, and it permits the user to simulate a much wider range of bioenergy, forestry, or agroforestry management systems than was possible with FORCYTE-10.

DESIGN CRITERIA AND MODELLING APPROACH

A number of design criteria guided the development of:

FORCYTE-11:

1. The model should have a sufficiently generalized structure that it can be applied to a wide variety of even-aged stands managed under monoculture, mixed species, or alternating species forest crop (traditional or bioenergy) or agroforestry management systems. It should provide a modelling framework that can be "customized" for a wide variety of uses, rather than a single, fixed-structure model.

2. The model should have a modular structure that separates the calibration and testing of individual ecosystem component modules from the evaluation and use of the ecosystem management simulator. This structure also keeps the size of the management simulator within reasonable limits, and reduces the problem of model size and complexity that normally limits the amount of detail that can usefully be added to an ecosystem-level model.

3. The model should provide the user with the opportunity to simulate the effects of all the major management treatments on nutrient cycling, soil nutrient availability, and competition for nutrients and light. The effects of these site resources on plant growth and the relative competitive abilities of different species should be simulated explicitly.

4. Ecological processes that determine growth should be simulated as mechanistically as possible, avoiding the use of artificial mathematical surrogates which do not have an ecologically or biologically sound theoretical basis.

5. The model should, wherever possible, be driven by empirical, inventory-type data, rather than by data on process rates that require prolonged and detailed scientific measurement. Although the requirement for field, growth chamber, or laboratory measurements of the rates of some processes is unavoidable, inventory- type data should be employed wherever it is possible. Achievement of this design criterion depends on the combination of a field-measurement of the outcome of some process (e.g. annual growth of plants; annual weight loss of a decomposing log) with an understanding of that process. This combination is used to infer the rate at which the process must have occurred. Thus, many process rate estimates are obtained indirectly from field inventory-type data.

6. The modelling approach should be that of hybrid simulation: the presentation of the historical patterns of plant growth and

ecosystem function, and an evaluation of the repeatability of these patterns when the rates of certain processes are changed by the simulation of altered management practices.

7. The model should produce sufficient diagnostic output to permit the user to identify errors in data entry, "bad" data, or unacceptable model performance. This diagnostic output should be produced by each of the model's subcomponents, and should provide a useable basis for model (or individual module) rejection.

8. Wherever possible, the user should have the option to switch off or alter the simulation of individual processes where he/she does not accept the way these processes have been simulated. This provides the user with a means of modifying many of the model's assumptions. The user must have control over all process rates by way of input data files.

9. The number of calibration "twiddle knobs" should be kept to an absolute minimum, and where these are inevitable, they should be controlled by the user in the input file. They should not be "hidden" in the code. As few assumptions as possible should be embedded in the computer code: wherever possible, assumptions should be controlled by the user via the input data files.

Details of the modelling approach will not be presented here as they have been presented in Kimmins (1985, 1986 and 1988) and Kimmins and Scoullar (1989). Details of the supervisory software package PROBE that facilitates the use of the model in multiple comparison runs (Kurz et al. 1987), and the presentation and interpretation of the output of these runs (Appe et al. 1988, McIsaac et al. 1989) have been presented elsewhere.

STRUCTURE AND PROCESSES REPRESENTED

Details of the structure and processes of FORCYTE-11 can be found in the User's Manual (Kimmins and Scoullar 1989). By way of summary, the structure of this version of the model is presented in Figure 1, while the major compartments and processes that are simulated are shown in Figure 2. The simulation options and processes that are represented in the benchmark version of FORCYTE-11 are listed in Table 1.

A. Management Options Available to the User of the Benchmark Version of FORCYTE-11.

- Site preparation: manual weeding, broadcast slashburning.
- Regeneration: planting, natural seeding, vegetative reproduction (root suckering or coppice sprouting); regeneration of single or multiple-species crops.
- Weed control - manual.
- Stocking control - precommercial thinning (spacing).
- Nurse crops - Nitrogen-fixing herbs, shrubs or trees.
- Stand maintenance - control of non-crop species. - control of species composition.
- Fertilization - single or multiple nutrients.
- Commercial thinning - high, low or random thinning. Any utilization level.
- Final harvest - clearcutting, shelterwood, or seed tree method with any utilization level.
- Utilization level: stem only, "whole tree" (above-ground), or "complete tree" (above- plus below-ground), or any intermediate level.

B. Natural Disturbance Events That Can Be Simulated.

- Wildfire - effects of wildfire on ecosystem organic matter and nutrients.
- Herbivory - insect defoliation of canopies, wildlife browsing of seedlings, domestic livestock grazing of competing vegetation.

C. Processes That Can Be Simulated.

- Photosynthesis and "foliage nitrogen efficiency".
- Plant growth and biomass accumulation.
- Nutrient limitation of growth.
- Litterfall - above-ground and below-ground.
- Foliar leaching.
- Plant competition for light and nutrients.
- Effects of shading on photosynthesis: sun and shade foliage.
- Effect of shading on height growth.
- Plant mortality - density-dependent mortality (stand self-thinning, or shading by competitors) and density-independent mortality. - Winter photosynthesis - evergreen photosynthesis when deciduous competitors are leafless.
- Geochemical cycle - inputs and outputs of nutrients to and from the ecosystem: precipitation, weathering, nitrogen fixation, fertilization, soil leaching, harvest removals.
- Biogeochemical cycle - uptake, litterfall, foliar leaching, decomposition (mineralization/immobilization).
- Internal cycling - retranslocation of nutrients at the time of tissue senescence.

- Decomposition - loss of organic matter and nutrient mineralization and immobilization.
- Effect of clearcutting on decomposition.
- Soil leaching.
- Soil exchange capacities.

CONCLUDING STATEMENT

Although the capabilities of FORCYTE-11 have expanded the scope of the original project, the objective of the model has not changed: to be able to make short, medium, and long-term predictions concerning the yield, the sustainability of yield, the economics, and the energy efficiency of a wide range of alternative bioenergy management strategies. Initially a main-frame model, FORCYTE now runs on 386-based microcomputers making the model more accessible.

A model is limited by its performance and ease of use. Major improvements have been made in the latter by the development of the PROBE package of software (Figure 1), and further development in this area is progress (McIsaac et al. 1989). Verification and validation projects are planned or in progress (Grewal et al. 1989, Peterson and Apps 1989, Pike and Meades 1989, Sachs et al. 1989), and a group of cooperators willing to field test the benchmark version of FORCYTE-11 has been identified. It is planned to report on the results of this activity in both 1990 and 1991.

ACKNOWLEDGEMENT

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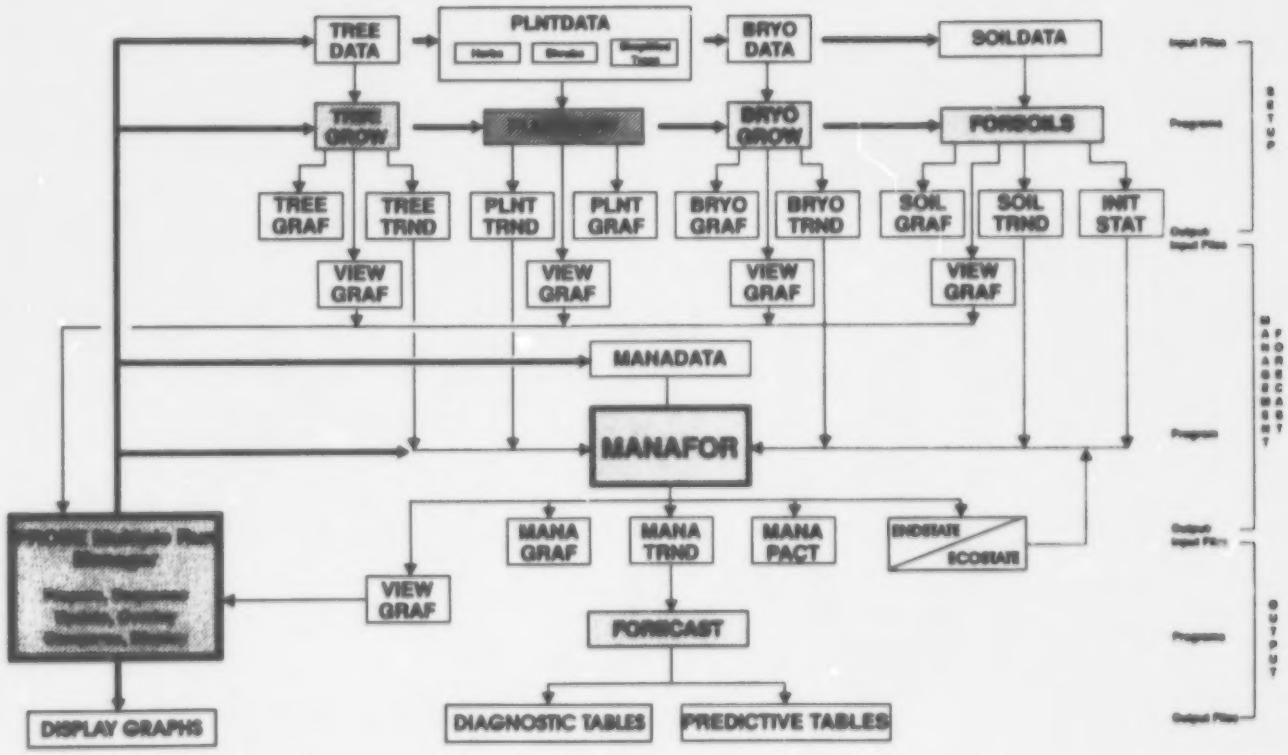


Figure 1.: The overall file and program structure of the FORCYTE- 11 modelling framework. Users can assemble the appropriate "setup" modules to produce a simulation of any particular forest or agroforesty ecosystem. The relationship between the PROBE supervisory software and the FORCYTE framework can be seen.

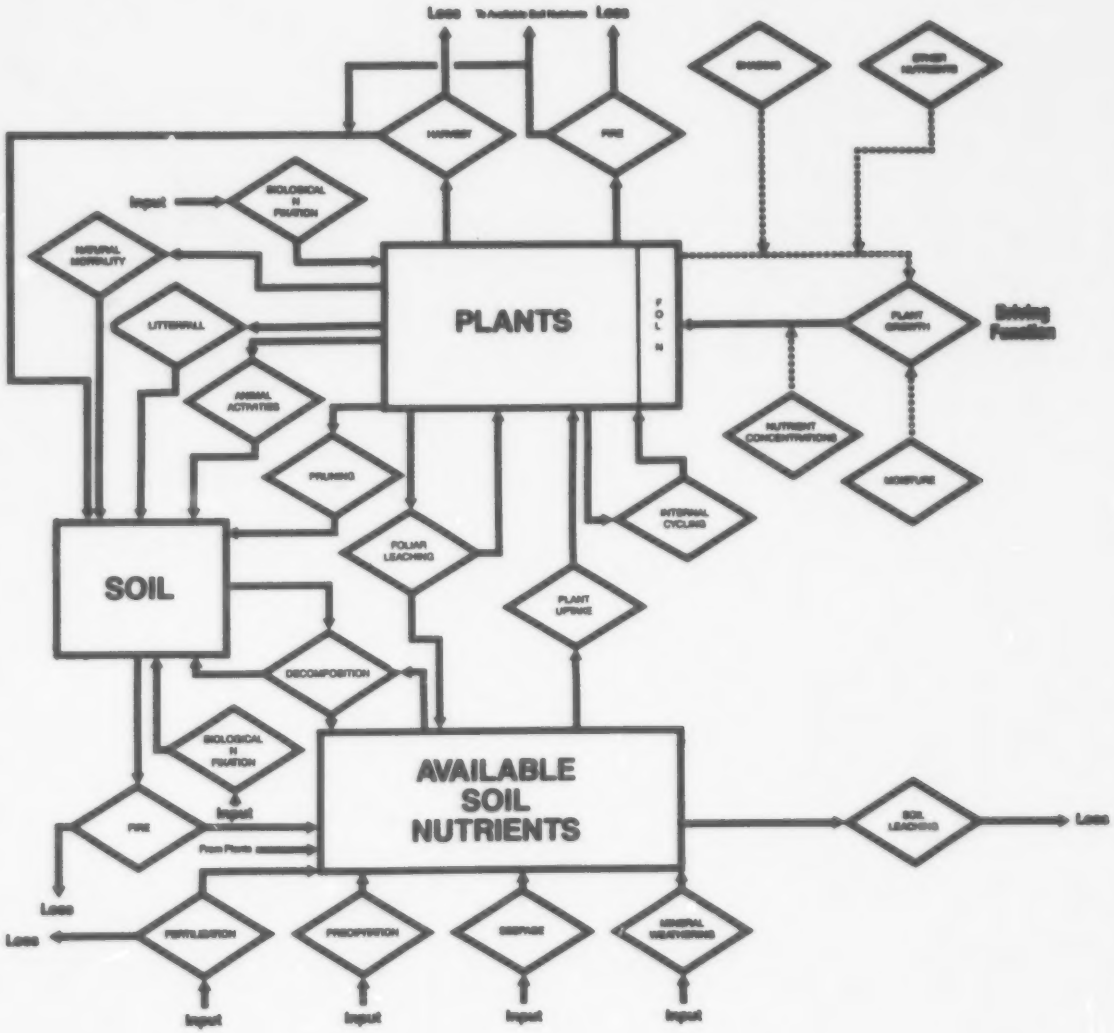
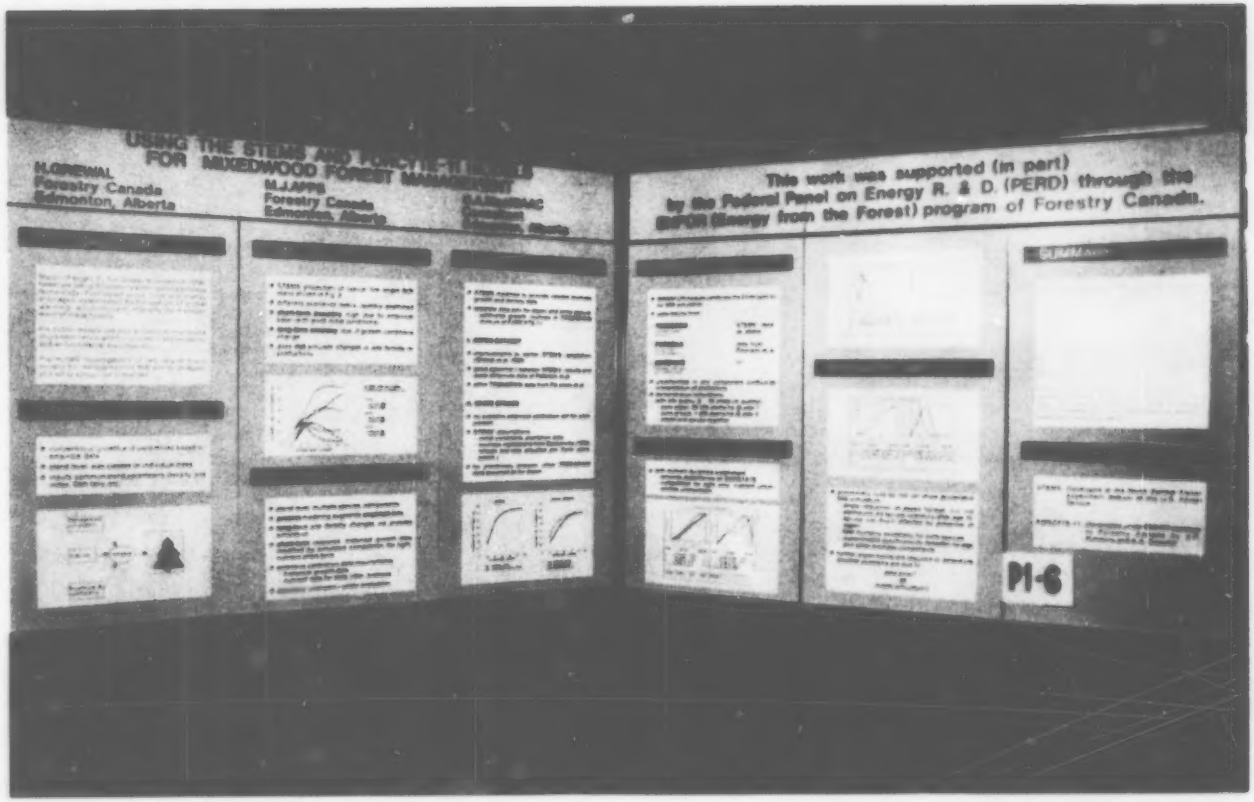


Figure 2. Major compartments and processes that are operational in the benchmark version of FORCYTE-11. Some of the processes shown in earlier published versions of this diagram are not available in this benchmark version, but are expected to be available in future versions.


FOR MIXEDWOOD FOREST
Forestry Canada
Edmonton, Alberta
Forestry Canada
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P1-6

USING THE STEMS AND FORCYTE-11 COMPUTER MODELS FOR MIXEDWOOD FOREST MANAGEMENT

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There is an increasing need for management tools for forests of trembling aspen (Populus tremuloides Michx.) and white spruce (Picea glauca Moench [Voss]) in western Canada. Traditional growth and yield methods based on data from unmanaged stands may be inadequate for forecasting yields resulting from the expected new approaches to mixed stand management.

FORCYTE-11 is a large forest ecosystem simulation model that can be used to predict and to compare forest biomass growth and yield for alternative resource management strategies for which there may be little or no direct empirical data. It permits the inclusion of more than one tree species and accounts for inter- and intra- species competition for light and nutrients. However, the input data required to calibrate the model may not be easily available or may be expensive to collect. An alternative approach is described in which a traditional growth and yield model (STEMS) has been modified to provide the needed ecosystem description for FORCYTE-11. This method only requires the conventional stand parameters such as stand age, average stand Dbh, stand density, and site index.

Favourable preliminary results with calibrating FORCYTE-11 for aspen have encouraged us to extend this method to ecosystems. In this paper application of this approach to a range of site classes will be discussed. Because this approach requires only commonly available stand parameters, it can potentially provide a practical link of FORCYTE-11 to regional databases through geographic information systems.

On a de plus en plus besoin d'outils de gestion utilisables dans le cas des forêts mélangées de tremble (Populus tremuloides, Michx.) et d'épinette blanche (Picea glauca Moench [Voss]) dans l'ouest du Canada. Les méthodes traditionnelles de calcul de la croissance et du rendement basées sur des données recueillies à partir de peuplements non gérés peuvent se révéler inadéquates pour prévoir les rendements résultant de l'application de nouvelles approches de gestion des peuplements mélangés.

Le FORCYTE-11 est un important modèle de simulation de l'écosystème qui peut servir à prévoir et à comparer la croissance et le rendement de la biomasse forestière que l'on obtiendraient avec diverses stratégies de gestion des ressources sur lesquelles on ne possède pour ainsi dire pas de données empiriques directes. Ce modèle permet l'inclusion de plus d'une essence et tient compte de la compétition interspécifique et intraspécifique pour ce qui est de la lumière et des éléments nutritifs. Toutefois, l'obtention des données nécessaires pour étalonner le modèle peut se révéler difficile ou coûteuse. On décrit une autre aproche dans laquelle un modèle classique de croissance et de rendement (STEMS) a été modifié pour fournir la description de l'écessaire au FORCYTE-11. Avec cette méthode, il suffit de connaitre les paramètres classiques liées au peuplement, comme l'âge du peuplement, le Dhh moyen pour le peuplement, la densité du peuplement et l'indice de station.

Les résultats préliminaires favorables obtenus avec l'étalonnage du FORCYTE-11 appliqué au tremble nous ont encouragés à appliquer cette méthode à des écosystèmes mélangés. Dans ce document, on traite de l'application de cette approche à une variété de classes de site. Comme cette approche ne nécessite que les paramètres relatifs aux peuplements dont on dispose normalement, elle pourrait servir de lien pratique entre le FORCYTE-11 et les bases de données régionales grâce à des systèmes d'information géographiques.

INTRODUCTION

The forests of the boreal mixedwood (MW) region contain a mix of heterogeneous ecosystems. Stand composition varies from pure hardwoods, dominated by aspen (Populus tremuloides Michx.), to pure softwoods, of which white spruce (Picea glauca Moench [Voss]) is commercially the most important. A full spectrum of mixtures of sizes and percentages of these two species exist between these extremes. The variation in stand composition is due mainly to site history (particularly the occurrence and severity of fires) as well as site and soil conditions.

Traditionally, white spruce has been favoured by the forest industry while aspen was considered a "weed" species. Improvements in harvesting and processing technology, however, have increased the potential for aspen utilization as indicated by recent announcements of new mill projects in western Canada, particularly in the province of Alberta. Moreover, forecasted global wood supply shortages will increase the incentives to use all major boreal MW tree species as sources of wood, fibre and energy. These pressures are compounded by environmental concerns such as global climatic warming and acid rain. Counterbalancing the need to maximize economic return from the forest is a growing requirement to ensure long-term sustainability and to minimize undesired environmental effects.

These pressures, together with the complexity of the MW forest itself, present a cogent challenge to the manager of the MW forest; he truly must be armed with a powerful crystal ball. In the absence of such omniscience, simulation models may be the best tools for predicting the results of today's decisions on tomorrow's forests. With appropriate models, different scenarios (e.g., management alternatives to meet changing economic, political, or environmental objectives) may be examined for both short-term returns and their longer-term consequences. Such information will be increasingly needed to help the decision-maker make more informed choices.

In this paper preliminary work with two models which have potential application to MW forest management is presented. STEMS (Stand and Tree Evaluation and Modeling System, U.S.D.A. Forest Service, 1979) is a conventional growth and yield model built on a large empirical database. FORCYTE-11, discussed elsewhere in these proceedings, is a more flexible, but more complex, model which employs both process simulation and empirical biomass chronosequence data. We also describe initial attempts to use a modified PC version of STEMS (STEMS*, Grewal *et al.* 1989) to provide the empirical biomass data required to calibrate FORCYTE-11 for white spruce - aspen MW stands.

STEMS MODELING OF MIXEDWOOD STANDS

The projected development of a typical MW stand of fire origin was performed with STEMS. As a simple example of how the model might be used to assist management decisions, the effect of site quality on the relative performance of the two species was examined. Three sites, ranging from site index[1] 12m to 24m for spruce, were compared. Initial stand conditions emulate aspen with an understorey of spruce which is 10 to 20 years younger (Johnson 1986):

aspen: 2500 stems/ha, 9 cm average Dbh, at year 30
white spruce:6200 stems/ha, 4 cm avg Dbh, year 30

Normal size class distributions were assumed for both species using the treelist generation program TREEGEN of TWIGS, the PC version of STEMS described by Miner *et al.* (1989).

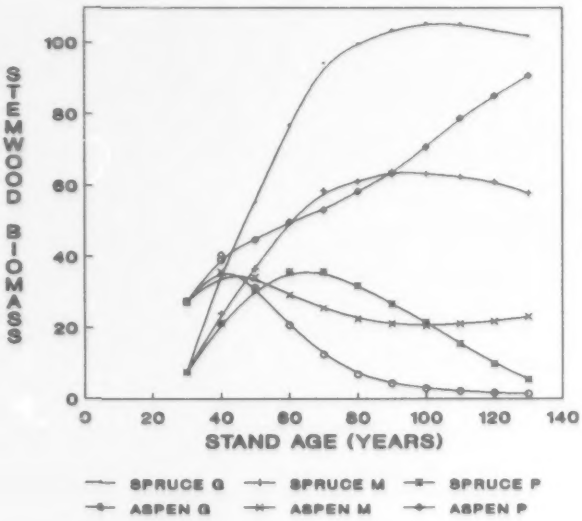

FIGURE 1: STEMS projections of stemwood biomass for white spruce and aspen on three sites. GOOD: SI=24M MEDIUM: SI=18M POOR: SI=12M. (biomass in t/ha)

The medium site shows the response often observed in MW stands - the aspen biomass peaks at about age 40 with the white spruce assuming dominance to reach its maximum 40 to 50 years later (Figure 1). This response is even more pronounced on the good site, but on a poor site, the spruce has a difficult time competing with the aspen over the entire rotation.

Although these results are in keeping with current management thinking (i.e., spruce regeneration on poor MW sites is uneconomic), they must be qualified. For simplicity, we have ignored early stand development and assumed the same stocking densities and size classes at year 30, a situation that is unlikely in reality. STEMS is limited by the availability of suitable regression equations used and the paucity of good regression coefficients for

[1]Site index, a common measure of site productivity and one of the parameters used in STEMS, is the average height of the dominant and co-dominant tree at the reference age of 50 years.

small biomass classes impedes its use for very young stands. Unfortunately, there is good evidence that the early development and inter-species competition in multiple species stands can be very significant to the eventual development of the stand. Correcting this difficulty in STEMS is beyond the scope of this paper.

STEMS assumes that the site productivity (site fertility conditions) does not change when management treatments (e.g., harvest, release of spruce from aspen, etc) are carried out. Its projections are based on the historically observed tree growth patterns, averaged over many stands and not on simulation of processes such as nutrient dynamics. It is thus not well suited to investigate long-term impacts on the site, or to predict the results of new silvicultural or harvest treatments which might create growth conditions for which there may not be empirical data.

FORCYTE-11 DATA NEEDS FOR MIXEDWOOD FORESTS

In contrast to STEMS, FORCYTE-11 is a complex model requiring considerable initial set up and calibration effort by the user. A hybrid stand-level yield simulation model, it bases its predictions on empirical data that describe the observed patterns of biomass accumulation in existing stands (historical bioassay (HB) data, Kimmins and Scoullar 1989). For a two species MW stand, such HB data is required separately for each tree species to be modelled in the management simulator MANAFOR and for a suite of site nutrient qualities representing the range of managed stand growth conditions. Additional nutrient and soils data is also required for each site as discussed in Grewal *et al.* (1989) and Kimmins and Scoullar (1989). These references also discuss the standard methods for calibrating FORCYTE-11, and the reasons and rationale for the use of STEMS* to short-cut this process.

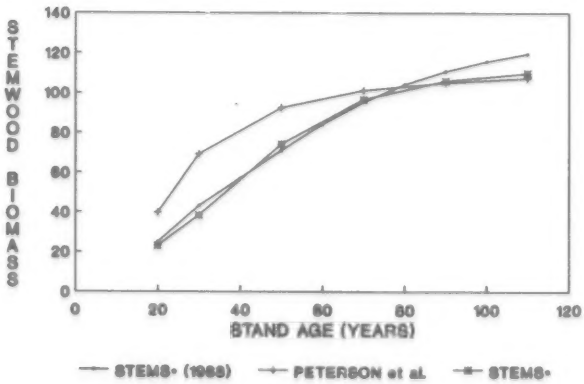

FIGURE 2: STEMS* projections vs data set from Peterson *et al.* 1988 for aspen stemwood biomass. STEMS* SI=17M Peterson Site Quality= 50
1988 STEMS* from Grewal *et al.* (1989) (biomass in t/ha)

Aspen Data Set

Since initially reported, STEMS* has been improved by inclusion of a new diameter adjustment function (Holdaway 1985). It now generates biomass accumulation curves which more closely match with the quasi-empirical (literature based) data assembled by Peterson *et al.* (1988). Data for stemwood biomass are shown in Figure 2 for a stand of 9900 stems/ha, average Dbh of 4.5 cm at age 20, and site index of 17m at age 50 years.

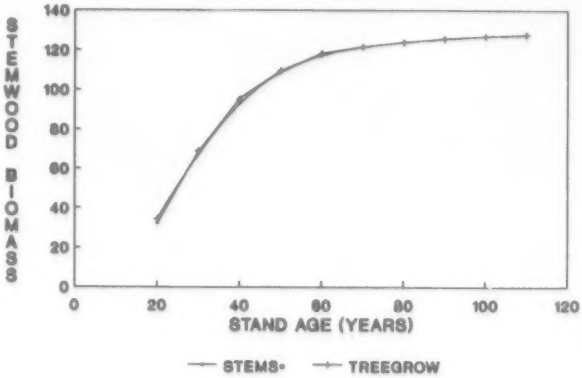

FIGURE 3: STEMS* vs TREEGROW projection for medium site white spruce stemwood biomass. (biomass in t/ha).

White Spruce Data Set

In the absence of an empirical calibration of FORCYTE-11 for white spruce, the STEMS* approach was used as follows. STEMS growth and mortality functions for white spruce, together with biomass equations for stemwood, stembark, foliage, and crown biomass components from Baskerville (1965), were incorporated in the modified white spruce STEMS* model. Initial monoculture stand conditions, from plantation data (Stiell and Berry, 1973), were used in STEMS* to generate the required biomass HB data from 20 to 115 years. The foliage biomass predicted by the Baskerville regression equations were unrealistically high, and were reduced using ratio factors obtained from Yarie's (1988) white spruce data set for FORCYTE-10. Other input parameters (photosynthesis, light saturation curves, tree heights, canopy thickness, etc.) were estimated from values in the literature and from the calibration of FORCYTE-11 for another conifer (Douglas-fir).

While the values obtained by the above process appear credible, the result must be considered a prototype calibration data set only. FORCYTE-11's TREEGROW subprogram uses these data to effectively parameterize the tree growth simulation sub-model. It also uses these calibrated routines to generate output diagnostic curves of simulated biomass, and other ecosystem component dynamics. When the prototype spruce data was used (Figure 3), most simulated biomass components appeared to track the original

data quite reasonably. This agreement does not validate the simulation; it does however indicate that the simulations are working plausibly.

FORCYTE-11 MIXEDWOOD SIMULATIONS

Simulation of a MW ecosystem using FORCYTE-11 is accomplished with the management simulator MANAFOR which combines the process simulation sub-models (calibrated within FORSOILS, TREEGROW, etc.). MANAFOR also requires a file called ECOSTATE which defines the initial state of the soil resource: ECOSTATE effectively integrates the site history prior to the start of the simulation. This pre-management set up activity (Kimmins 1988, Kimmins and Scoullar 1989) can complicate evaluation and verification of MANAFOR results. Uncertainties and errors in ECOSTATE, or any of the sub-model calibrations, can propagate through the MANAFOR program and confound interpretation of its predictions.

TREEGROW was calibrated by combining the aspen and white spruce data sets into a two-species TREEDATA file. Calibration of the FORSOILS sub-model used the soil data from the pre-existing aspen data set (Peterson *et al.* 1988) which was developed for the MW ecoregion in Alberta (the two species sharing the same soil stratum are assumed to compete for the available nutrients). The ECOSTATE file was constructed with a spruce-aspen simulation covering 3 rotations of 80 years each. In order to simulate the build-up of soil nutrient capital, about 30% of the biomass was left to decompose in the forest floor after each rotation.

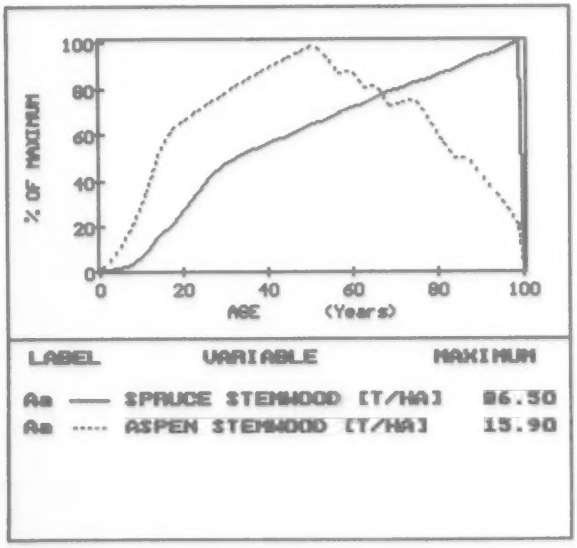

FIGURE 4: Aspen and white spruce stemwood biomass simulated by MANAFOR. Graph produced by PROBE Display Manager (MacIsaac *et al.* 1989.

To demonstrate model performance, a 100 year MW rotation was simulated. During the first year, 5 000 white spruce seedlings were planted and 90 000 aspen suckers were allowed to sprout. The spruce eventually dominates over aspen through competition for light and nutrients (Figure 4), in agreement with expected MW stand development. In addition, although the absolute values are of unknown accuracy, they are of the right magnitude. The model which is driven by the photosynthetic process through foliar nitrogen content, permits the success of the low density spruce through at least four mechanisms:- 1) longer retention of spruce foliage; 2) deeper spruce canopy development; 3) shade tolerant spruce foliage; and 4) less shade tolerant foliage for aspen.

In this simulation there was inadequate self-thinning of the spruce which may be related to the relative initial densities of the two species. This problem was significantly reduced when simulations were performed with nutrient limitation to growth disabled. It thus appears that the model (calibrated with the prototype MW data) puts more emphasis on competition for nutrients than for light.

We cannot unambiguously differentiate between data set errors or model inadequacies from the results to date. Before MW management simulations (planting regimes, release of spruce, thinning, etc.) can be attempted, further refinements of the prototype calibration must be made. In addition, the benchmark version of the FORCYTE-11 model was received after this manuscript was prepared and many of our concerns may be resolved when it is tested.

CONCLUSIONS

Preliminary investigations of two very different models, one an empirically-based conventional growth and yield model, and the other a hybrid simulator, have been performed. While both models can be used to assist forest managers in forecasting the results of today's actions on tomorrow's MW stands, they provide different levels of information, with different levels of certainty, and require different levels of user effort.

STEMS is easier to use and more believable in the short-term. However, it cannot account for changing site fertility conditions which could arise from intensive management or other factors such as climate change. In addition shortage of good regression equations for small biomass classes hinders its application to early stand development and inter-species competition, a problem of current MW management concern.

FORCYTE-11 permits greater flexibility for changing site growth conditions by including process simulation of competition for light and nutrients. However, it is both more complex to run and requires considerable site specific data. In addition, an assessment of the accuracy of its predictions has not yet been performed.

The preliminary use of STEMS* to provide part of the site-specific calibration data for FORCYTE-11 MW applications has been encouraging, but further work is needed before an adequately calibrated model is ready for application and evaluation.

ACKNOWLEDGMENTS

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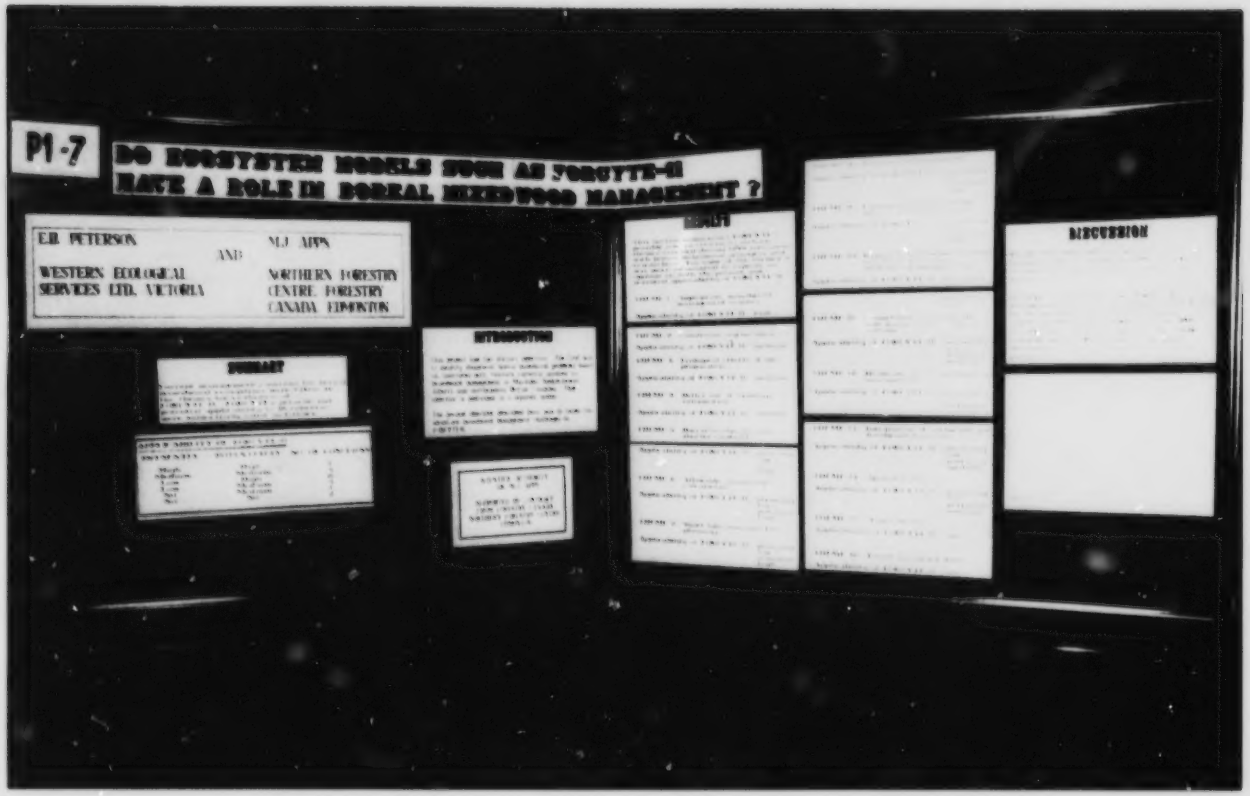
P1-7
DO ECOSYSTEM MODELS SUCH AS FORCYTE-11
HAVE A ROLE IN BOREAL MIXEDWOOD MANAGEMENT ?
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CANADA, EDMONTON
SUMMARY
INTRODUCTION
RESULTS
DISCUSSION

DO ECOSYSTEM MODELS SUCH AS FORCYTE-11 HAVE A ROLE IN BOREAL MIXEDWOOD MANAGEMENT?

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Current management concerns for boreal mixedwood ecosystems were taken as the points of focus for evaluation of FORCYTE-11. Applicability of FORCYTE-11 to the identified management concerns was judged from two vantage points - present applications and possible future applications. These assessments were based on professional knowledge of the modelling framework, tempered by judgements about how the model could find new applications in a setting where technical factors such as utilization, economics and climate, and social factors such as professional opinions and public perceptions, are rapidly changing. For only one of 16 identified concerns - need to define mixedwood management regimes - was FORCYTE-11 judged to have high applicability both presently and potentially. For three concerns (difficulty of white spruce regeneration, uncertain ecological effects of site preparation equipment, and inadequate use of existing information) applicability of the model was considered to be medium, now and in the future. There were three concerns with presently low but potentially medium applicability (competition from shrubs and grasses, restrictions to herbicide use, and integration of softwood and hardwood harvests). Concerns with presently low but potentially high application of FORCYTE-11 included: need to refine allowable annual cut calculations; nutrition management in boreal mixedwood ecosystems; energy production from mixedwood biomass; need for research to increase mixedwood productivity; development of short-rotation forestry; and the need to work with longer time horizons in forest planning. FORCYTE-11 was considered to have no present or foreseeable application for three identified concerns: management and use of decayed aspen; need for better inventory data for boreal hardwoods and understorey conifers; and the current lack of biophysical data at the scale at which operational decisions are made.

Les questions epineuses actuelles relatives a l'amenagement des ecosystemes boreaux melanges ont ete choisies comme points de mire pour l'evaluation du FORCYTE-11. L'applicabilite du FORCYTE-11 aux questions d'amenagement identifiees a ete jugee a partir de deux points de vue: les applications actuelles et les applications futures possibles. Ces evaluations etaient basees sur une connaissance professionnelle du cadre de modelisation, moderee par des jugements sur la facon dont le modele pourrait trouver de nouvelles applications dans un cadre ou les facteurs sociaux comme les opinions des professionnels et les perceptions du public, changent rapidement. Dans le cas d'un seul des seize problemes - la necessite de definir les regimes d'amenagement des forets melangees, on a juge que le FORCYTE-11 etait hautement applicable a la fois actuellement et potentiellement. Dans le cas de trois des problemes (difficulte de regenerer l'epinette blanche, incertitude quant aux effets ecologiques de l'equipement de preparation des sites et utilisation inadequate de l'information existante) on a considere que l'applicabilite du modele etait moyenne, actuellement et pour l'avenir. Dans trois autres cas (competition des arbrisseaux et des graminees, restrictions imposees a l'utilisation des pesticides et

integration des recoltes de coniferes et de feuillus), l'applicabilite s'est revelee faible pour le moment, mais potentiellement moyenne pour l'avenir. Parmi les problemes pour lesquels l'applicabilite du FORCYTE-11 est actuellement faible, mais potentiellement elevee pour l'avenir, on compte les suivants: besoin de raffiner les calculs des coupes annuelles permissibles; gestion nutritionnelle dans les ecosystemes boreaux de forets melangees; production d'energie a partir de la biomasse provenant de forets melangees; besoin d'effectuer des recherches pour accroitre la productivite des forets de bois melanges; mise au point de methodes de foresterie avec rotations courtes; et besoin de travailler avec des horizons plus longs dans la planification des forets. On a considere que le FORCYTE-11 n'etait pas applicable actuellement ni dans un avenir previsible dans le cas des trois problemes suivants: gestion et utilisation du tremble pourri; besoin ne donnees d'inventaires meilleures pour les feuillus boreaux et pour les coniferes de sous-etages; et manque de donnees biophysiques au niveau ou sont prises les decisions operationnelles.

INTRODUCTION

FORCYTE-11 (FORest nutrient Cycling and Yield Trend Evaluator), a stand-level ecosystem modelling framework, was developed under ENFOR contracts by Prof. J.P. Kimmins and co-workers at the University of British Columbia (Kimmins and Scoullar 1987). The boreal mixedwood region was selected by Forestry Canada as one of several areas in which to assess management and research roles for this modelling framework.

The present report is a result of a project that had two distinct objectives. The first was to identify stand-level boreal mixedwood problems based on interviews with foresters currently involved in mixedwood management. That objective is addressed in a separate report in these seminar proceedings (Peterson et al. 1989). The second objective, described here, was to relate the identified mixedwood management challenges to FORCYTE-11.

METHODS

To relate present concerns to the FORCYTE-11 modelling framework required the contractor's judgement of whether each identified mixedwood management theme might be served by this modelling framework, in its present state of development. The method adopted for this part of the project was very subjective. The recorded opinions about FORCYTE's applicability to a given mixedwood management concern are not the result of consensus-building during interviews because the latter focussed on problem definition rather than detailed discussions of the model.

IMPLICATIONS OF 1988 INTERVIEW INFORMATION FOR FORCYTE-11

This section examines FORCYTE's possible role in relation to sixteen themes revealed during 1988 interviews with boreal mixedwood managers and researchers. For some of the themes the subjective rating is considered to be the same now and in the future; for other themes FORCYTE-11 is considered to have a higher potential use than it has at present. The themes are listed in order of decreasing applicability of FORCYTE-11.

Theme 1: Appropriate mixedwood management regimes

Applicability to FORCYTE-11: high

Reasons for opinion: FORCYTE-11 is designed to simulate competition and the dynamics involved in two-species stands. FORCYTE's highest present and potential applicability lies in the many specific concerns about optimum mixedwood management. These problems involve planning periods of several decades, a time horizon that matches the intended purpose of FORCYTE-11.

Theme 2: Coniferous regeneration

Applicability of FORCYTE-11: medium

Reasons for opinion: Coniferous regeneration in mixedwood ecosystems is amenable to FORCYTE-11 simulation because in many cases it involves competition between two tree species (spruce and aspen). Furthermore, it is a challenge of longer duration than the shrub-grass

problem described in theme 11. Some respondents stressed that spruce regeneration is largely under the control of microsite differences which are at a spatial scale that cannot be addressed by a stand-level model such as FORCYTE; this is the reason for a medium rather than a high rating.

Theme 3: Ecological effects of site preparation

Applicability of FORCYTE-11: medium

Reasons for opinion: Slash management and the influences of site preparation activities on decomposition rates and nutrient cycling are subjects that can be simulated by FORCYTE-11. For those topics FORCYTE's present and potential applicability was rated as medium, rather than high, because respondents who expressed concern over site preparation effects focussed on variables that FORCYTE-11 does not address, such as changes to bulk density, aeration in the rooting zone, soil moisture and soil temperature, as well as successional changes in post-treatment vegetation.

Theme 4: Better use of existing information base

Applicability of FORCYTE-11: medium

Reasons for opinion: FORCYTE-11 is considered to have a role here, presently and in the future, because its calibration and use requires the user to assemble data and ecological information which might otherwise remain unapplied.

Theme 5: Boreal hardwoods and shorter rotations

Applicability of FORCYTE-11: presently low / potential high

Reasons for opinion: Because there is presently very little interest in short rotation management, it is premature to suggest a high applicability of FORCYTE. However, if there is a trend towards shorter rotations, the nutrient cycling and productivity consequences of such a trend are precisely the kinds of changes that FORCYTE was designed to simulate.

Theme 6: Allowable annual cut calculations

Applicability of FORCYTE-11: presently low / potential high

Reasons for opinion: At present, this concern reflects a data collection need which cannot be served by a simulation model such as FORCYTE. However, if long-range yield predictions become integral parts of allowable annual cut calculations for sustainable forestry then FORCYTE-11 could have a high applicability in the calculations.

Theme 7: Short time horizons for planning

Applicability of FORCYTE-11: presently low / potential high

Reasons for opinion: With short time horizons there is no reason for forest managers to be interested in the multi-rotation predictions that can be made with a calibrated FORCYTE dataset. However, the potential applicability of the model will be high once managers need to have forecasts of site conditions and productivity in the next rotation.

Theme 8: Nutrition management

Applicability of FORCYTE-11: presently low / potential high

Reasons for opinion: Nutrition management is the centrepiece of FORCYTE's original intent. Its applicability to nutrition management will obviously be high once nutrients become a concern amongst boreal mixedwood managers and researchers. Although there is little interest now in fertilization of mixedwood stands there are several unanswered questions that could be researched with the aid of FORCYTE. For example, will fertilizers be required to sustain productivity during subsequent rotations?

Theme 9: Energy production from boreal mixedwood biomass

Applicability of FORCYTE-11: presently low / potential high

Reasons for opinion: Energy values can be attached to any of the biomass components simulated by FORCYTE. The model can also compile the energy cost of silvicultural operations to produce the biomass. Potential applicability of the model for prediction of energy production, based on prediction of biomass production, could be important in the future even if it is not now.

Theme 10: Research and demonstration areas for increased mixedwood productivity

Applicability of FORCYTE-11: presently low / potential high

Reasons for opinion: FORCYTE-11 may find its greatest application as an education tool or as a research planning tool. Many models serve a function by forcing researchers to develop new hypotheses

about ecological processes in their search for model refinements.

Theme 11: Competition from shrubs and grasses after clearcutting

Applicability of FORCYTE-11: presently low / potential medium

Reasons for opinion: This is a short-duration problem in the overall life of a forest stand. Seasonal events or short-term dynamic changes that can be assessed directly by field observations are not high priority topics for a modelling approach and for this reason FORCYTE is considered to have only a medium potential applicability. The present applicability is judged to be low because calibration of the model for simulation of competition for nutrients or competition from shading would be hampered by lack of data. Furthermore, FORCYTE-11 does not simulate competition from moisture, nor is it designed to portray spatial representation, a feature involved in most competition indices developed to date.

Theme 12: Herbicide use in mixedwood management

Applicability of FORCYTE-11: presently low / potential medium

Reasons for opinion: Although FORCYTE could be calibrated to simulate the ecological effects of a shrub or herb understorey species, such information is more readily attainable by direct measurement rather than modelling, because it is part of the same short-term phenomenon referred to in Theme 11. In any case, the herbicide concern expressed by respondents is a public relations and regulatory problem, not an ecological problem for which FORCYTE-11 was designed.

Theme 13: Integration of softwood and hardwood harvests

Applicability of FORCYTE-11: presently low / potential medium

Reasons for opinion: This concern presently involves questions of costs, scheduling, and administrative or regulatory arrangements that seemingly have no relationship to the simulation capabilities of FORCYTE. However, the model may have application because of its ability to simulate sizes of individual stems and to attach economic values to biomass components of various sizes. Diameters of raw materials and the economic values associated with logs of various sizes can help define optimal uses of softwood and hardwood components.

Theme 14: Spatial scale

Applicability of FORCYTE-11: presently nil / potential medium

Reasons for opinion: This concern is considered to be a data collection problem as in theme 16, with no obvious contributions from a modelling approach. However, if FORCYTE is used in the future as a trend evaluator for certain biomass or nutrient variables that are recorded in a geographic information system, then the model could help to identify data collection needs.

Theme 15: Aspen decay

Applicability of FORCYTE-11: nil

Reasons for opinion: Decay management involves silvicultural and clonal manipulation, genetic selection and changing utilization standards, none of which have obvious present or potential relationships to FORCYTE's simulation capabilities.

Theme 16: Forest inventory data

Applicability of FORCYTE-11: nil

Reasons for opinion: This concern is a data collection requirement for which FORCYTE is not applicable.

DISCUSSION AND CONCLUSIONS

FORCYTE-11 and today's time horizons for forest planning

Although sustainable forestry is advocated by an increasing number of analysts, the 1988 interviews did not reveal much interest amongst managers for long planning horizons. Comments from several respondents did reveal an understanding that if we are to manage the mixedwood forest it is important to know something about the genetic and ecological blueprint that sustained these ecosystems up to now. But no respondents went the extra step to encourage the use of models such as FORCYTE-11 for prediction of how simulated management alternatives relate to the basic blueprint.

Links between FORCYTE-11 and forest site classification

Interviews revealed potential links between the geographically-oriented focus of forest site classification and the time-oriented focus of ecologically-based computer simulations. Developers of the FORCYTE-11 modelling framework (Kimmins and Scoullar 1987) recognized that to deal with the variability that exists

over large management areas it is necessary for forest managers to consider variation in space as well as variation in time. To aid in the understanding of spatial variation, ecosystem classification systems such as those developed for west-central Alberta (Corns and Annas 1986) and Saskatchewan (Kabzems et al. 1986) are used. Variations in time are the explicit role of models such as FORCYTE-11.

The FORCYTE-11 modelling framework requires the user to provide vegetational and soil data on a site-specific basis. Up to five different site qualities or ecosystem types can be calibrated in the input files. Thus, use of FORCYTE-11 establishes an obvious link with site classification data.

The prospect for use of FORCYTE-11 by forest managers

The 1988 interviews led to the general conclusion that a modelling framework such as FORCYTE-11 will not be applied operationally until site classification systems are in widespread use. This will not happen quickly because site classification faces its own problems of acceptance by forest managers. In addition to this dependency on the acceptance of site classification, FORCYTE faces two other deterrents to its use: a relative lack of concern by forest managers in the processes that the model simulates; and the model's complexity.

The FORCYTE-11 modelling framework was designed to simulate several forest management activities that do not appear to be of much interest yet to managers in the Mixedwood Section - fertilization and thinning are the most obvious examples. This poses at least temporary limitations on the degree to which FORCYTE can be applied in the boreal mixedwood context.

Predictions from complex models are difficult to check because of limited data on actual events over several decades of forest ecosystem development. This limitation will remain as long as there is little activity or interest in nutrition management in boreal mixedwoods; without such interest there will not be information with which to judge the reasonableness of FORCYTE's predictions. FORCYTE's intended roles of simulating forest nutrient cycles and predicting long-term consequences of intensive biomass harvesting will be more readily evaluated in forest regions where fertilization and nutrition management are already operationally implemented. For example, those forest ecosystems of British Columbia and the Pacific Northwest in which fertilization is now a part of forest management are better sites for evaluation of FORCYTE than are the less intensively managed boreal mixedwoods.

ACKNOWLEDGEMENT

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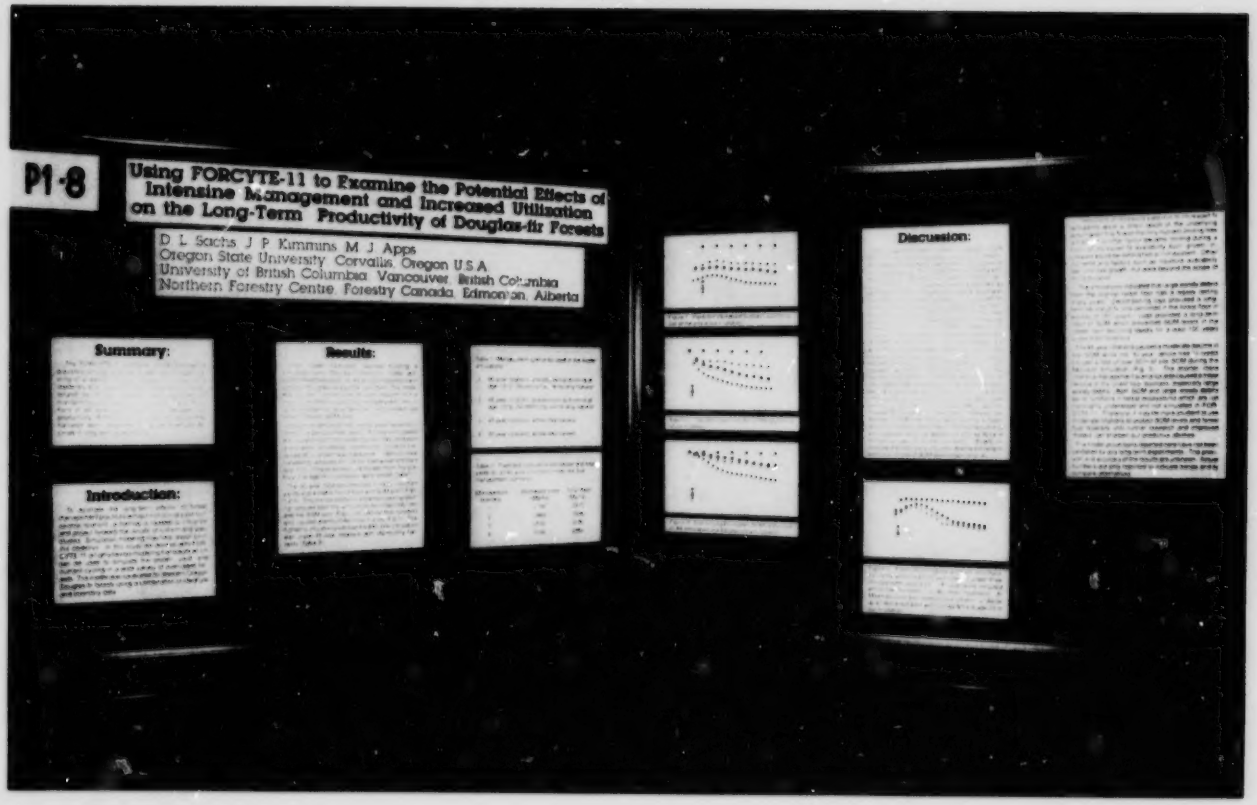
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Using FORCYTE-11 to Examine the Potential Effects of Intensive Management and Increased Utilization on the Long-Term Productivity of Douglas-fir Forests
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Summary:
Introduction:
Results:
Discussion:

USING FORCYTE-11 TO EXAMINE THE POTENTIAL EFFECTS OF INTENSIVE MANAGEMENT AND INCREASED UTILIZATION ON THE LONG-TERM PRODUCTIVITY OF DOUGLAS-FIR FORESTS

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As the demand for forest products escalates, forest managers are increasingly concerned about the possible detrimental effects of intensive management and increased biomass utilization on the long-term productivity of forest lands. The best estimate of the effects of current or planned management practices on future site productivity comes from multi-rotation long-term experiments. However, forest planners require more immediate estimates for allowable cut determinations. In addition, increased public awareness of the planning process requires that forest managers address the problem now. Simulation modeling can provide a means to integrate and project forward the results of current studies. The FORCYTE-11 computer simulation model has been calibrated for Douglas-fir forests using literature and inventory data. It is being used to examine the consequences of shorter rotations, increased biomass utilization, and slash burning on the long-term productivity of good and poor quality Douglas-fir sites. Current plans are to use the model to rank the projected effects of different management scenarios on long-term site productivity in preparing 10-year management plans for western Oregon.

Au fur et à mesure que la demande de produits forestiers monte en flèche, les gestionnaires forestiers sont de plus en plus préoccupés par les effets néfastes possibles de l'aménagement intensif et de l'utilisation accrue de la biomasse sur la productivité à long terme des forêts. La meilleure estimation de effets des pratiques de gestion actuelles ou prévues sur la productivité future des sites dont on dispose a été fournie par des expériences de multi-rotation à long terme. Toutefois, les planificateurs forestiers ont besoin d'évaluations plus immédiates pour déterminer quelles sont les coups permissibles. En outre, la conscientisation du public en ce qui concerne le processus de planification exige que les gestionnaires forestiers résolvent ce problème dès maintenant. Les modèles de simulation peuvent constituer un outil d'intégration et d'extrapolation à partir des résultats des études courantes. Le modèle de simulation par ordinateur FORCYTE-11 a été étalonné pour être applicable aux forêts de pin Douglas grâce à des données recueillies dans la documentation et dans des inventaires. Il servira à étudier les conséquences de rotations plus courtes, de l'utilisation accrue de la biomasse, et du brûlage de rémanents sur la productivité à long terme des forêts de pin Douglas de bonne et de mauvaise qualité. Actuellement, on cherche à utiliser le modèle pour classer les effets prévus de différents scénarios d'aménagement sur la productivité à long terme des sites, dans le cadre de la préparation de plans d'aménagement décennaux dans l'ouest de l'Orégon.

INTRODUCTION

In order to estimate the long-term effects of forest management practices without monitoring yield over several rotations, a method is needed to integrate and project forward the results of current and past studies. Simulation modeling can provide such a method and enable land managers to predict the long-term consequences of various silvicultural practices. In addition, models provide researchers a method to integrate existing knowledge and to test hypotheses.

In this study we worked with FORCYTE-11, a highly flexible modeling framework which can be used to simulate the growth, yield, and nutrient cycling in a wide variety of even-aged forests (Kimmins 1988; Kimmins and Scoullar 1984). FORCYTE-11 was calibrated to simulate the growth of Douglas-fir forests in Western Oregon using a combination of literature and inventory data. The growth and nutrient cycling of the understory vegetation was not simulated for this project.

FORCYTE-11 tracks the biomass and nutrient content of all decomposing tree and understory

components separately. Each type of material begins with a specified nutrient content as litterfall and decomposes for a specified number of years after which the remaining material becomes soil organic matter (SOM). The nutrient content of decomposing material approaches that of SOM as it decays. Decomposition rates can vary with both the age of the material and site quality. The decomposition rates for forest floor materials and SOM, and the nutrient concentrations of all materials are slightly higher on better sites in our data set. In FORCYTE-11 the decomposition rates of all materials can change after clearcutting and gradually return to pre-harvest levels as crown closure is reached. Based on data from Erickson et al. (1985) we slowed the decomposition of branches by 20% after clearcutting. Lacking any other data, we set the remaining decomposition rates to remain constant after clearcutting.

Initial model calibration requires building a simulated forest floor. This was accomplished by running the model with nutrient feedback disabled, allowing simulated growth to match that predicted by the input data. The model was run for seven consecutive 90-year rotations in this manner. At this point the forest floor contained litter in various stages of decomposition, including many logs, and the SOM pool reached steady state. The model was then used to test the effect of rotation length, increased biomass utilization, and slash burning on long-term site productivity. Rotation lengths of 90, 45, and 30 years were simulated for a period of 540 years. All rotations started with a planting of 1500 seedlings/ha. Two utilization levels were considered. Stems-only utilization removed 85% of stem wood and bark at harvest. Whole-tree harvesting removed 90% of the stem wood and bark and 70% of the branches and foliage from the site. The 90-year rotation was chosen to represent low intensity forestry. The 45-year rotation is similar to that being considered on forest industry lands in the Coast Range of Western Oregon. The 30-year rotation represents extreme biomass harvesting. Four management scenarios were tested:

1. 90-year rotations, pre-commercial thinning age 15 to 750 stems/ha, stems-only harvest
2. 45-year rotations, pre-commercial thinning age 15 to 750 stems/ha, stems-only harvest
3. 45-year rotations, whole-tree harvest
4. 30-year rotations, whole-tree harvest

In addition, scenario 4 was repeated with a moderate slash burn added prior to the initial rotation. This simulation was repeated with fertilization using 200 kg N/ha at age 20 in every rotation.

RESULTS AND DISCUSSION

As expected, the 90-year rotations resulted in fairly constant yields, a stable forest floor, and SOM pool (Figs. 1a,b,c). This was not surprising since the initial forest floor was built using 90-year rotations. The shorter rotations and whole-tree harvesting reduced both the amount of decomposing litter and the SOM pool (Figs. 1b,c). This seemed plausible since shorter rotations and increased utilization removed biomass that would have been deposited on the forest floor and eventually enter SOM

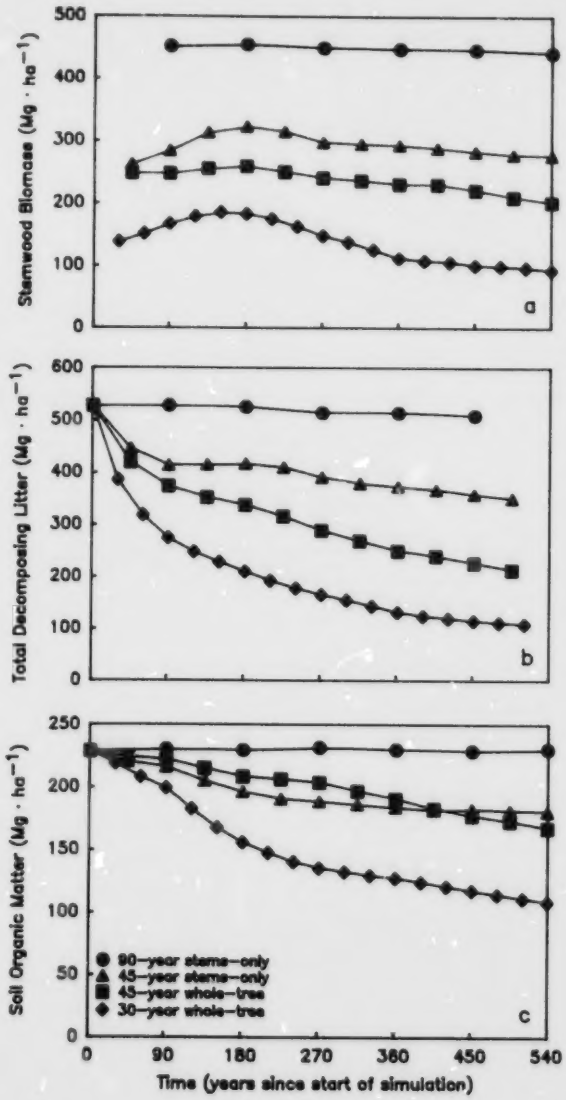

Figure 1. Projected effect of four management systems on forest system behavior over a 540-year simulation. (a) Stemwood biomass accumulation at the end of each rotation. (b) Total decomposing litter at the beginning of each rotation. (c) Total soil organic matter at the start of the simulation and the end of each rotation.

TABLE 1. Predicted cumulative stemwood and total yields for a 540-year simulation under the four management scenarios.

Management Scenario	Stemwood Yield (Mg/ha)	Total Yield (Mg/ha)
1.	2290	2570
2.	2980	3390
3.	2550	3150
4.	2220	2860

through decomposition. The whole-tree harvests also caused eventual declines in yield (Fig. 1a). The greatest cumulative biomass yield over the 540-year simulation came under 45-year rotations with stems-only harvesting (Table 1). The whole-tree harvest scenarios did not include a pre-commercial thinning. The difference in the predicted stemwood biomass production between the 45-year stems-only scenario and the whole-tree harvest scenario in the first rotation was due to the effect of pre-commercial thinning (Fig. 1a).

The amount of available soil N often increased during the first 150-180 years under the more intensive management scenarios, after which it decreased, often to levels below those of the first rotation. The initial increase in available soil N caused yield to increase for the first several rotations under short rotation management (Fig. 1a), and then eventually drop in later rotations as available N decreased. This effect in the model was caused by an interaction between two factors. Increased removal of tree biomass decreased forest floor biomass (Fig. 1b) which reduced the amount of N immobilized annually by forest floor decomposition. This left more available N for uptake by plants (cf. Vitousek and Matson, 1984). However, the increased biomass removals eventually lowered the input to SOM. As the amount of SOM decreased, the amount of N mineralized by SOM decomposition dropped, causing a decrease in available N in later rotations.

We simulated a moderate burn before the initial rotation of management scenario 4. The model predicted an earlier peak and more rapid decline in yield than with no burn (Fig. 2). The burn immediately removed a portion of the forest floor causing a decrease in N immobilization and increased N availability for tree growth. However, the decline in SOM was more rapid causing a faster decline in yield than with no burn.

We repeated the initial burn and 30-year rotation scenario with the addition of 200 kg/ha N in fertilizer at age 20. The fertilizer increased growth dramatically, but a slight downward trend in yield due to loss of SOM was evident (Fig. 2).

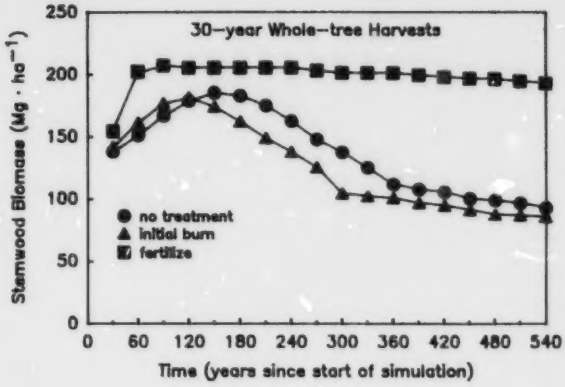

Figure 2. Predicted stemwood biomass accumulation at the end of each 30-year rotation under three management scenarios. All scenarios included whole-tree harvests. 1. No other treatment. 2. Moderate slash burn before initial rotation. 3. Same as 2., but fertilization with 200 kg N/ha at age 20 in each rotation.

In our simulations N availability varied by as much as 30 kg/ha between the highest and lowest yielding rotations. In a simulation exercise to examine the response of northern forests to climatic change, Pastor and Post (1988) found that their LINKAGES model predicted changes in forest vegetation type which altered soil N availability by as much as 40 kg/ha over a 500-year period. Hence, the changes in forest floor mass caused by shorter rotations and whole-tree harvests predicted by FORCYTE-11 might also affect N availability.

The predictions of increased yields during the first several rotations under more intensive management or from fertilization were a direct result of the underlying assumption that N was the only nutrient limiting tree growth. If another factor were to become limiting during the flush of increased N availability such growth responses would be diminished or perhaps not occur at all. The FORCYTE-11 model can simulate the cycling of several nutrients simultaneously and we plan to include other nutrients in future simulations. Certainly factors other than nutrient availability, such as soil moisture, can limit growth, but these are beyond the present scope of FORCYTE-11.

The model projections indicate that large woody debris from the last rotation can have a legacy often lasting many years. Decomposing logs provide a source of nitrogen and SOM often lasting in excess of 300 years (Sollins et al. 1987). It is the large woody debris from the original forest floor which is a long term input to SOM in the model. This prevents SOM levels from declining rapidly for at least 100 years under intensive management.

Model predictions of declining SOM levels caused by shorter rotations and increased utilization are consistent with agricultural experience. Voroney et al. (1981) measured losses of organic C resulting from 70 years of cultivation of the native Saskatchewan prairie. They reported an average of 38% of the organic C was lost from the soil profile. Van Veen and Paul (1981) modelled organic C dynamics in grassland soils. Their model showed sharp decreases in soil C as a result of cultivation of native grassland with C levels eventually stabilizing after 300-400 years.

CONCLUSIONS

The FORCYTE-11 model provides a plausible simulation of the growth and N cycling of a western Oregon Douglas-fir stand on a moderate site. Low intensity management characterized by 90-year rotations are projected as maintaining yield levels and site productivity. The model predicts that rotations of 45 years do not seriously degrade site productivity. Short rotations and whole-tree harvests are predicted to cause eventual declines in long-term productivity.

The 45-year, stems-only management scenario is projected as causing a 21% decline in site SOM while the 30-year whole-tree harvesting scenario caused a 53% decline over a 540-year period. The shorter, more intensive management scenarios also caused a major decline in the forest floor biomass, especially large woody debris. Both SOM and large woody debris serve functions in the forest ecosystem which are not thoroughly understood and not simulated in FORCYTE-11. For example, decaying logs can provide habitat for small mammals, including species important in dispersal of mycorrhizal spores critical for stand reestablishment (Maser et al. 1978;Franklin et al. 1981). Therefore, it may be more prudent to use more moderate rotations to protect SOM levels and provide some forest floor diversity until further research and improved models can sharpen our predictive abilities. It certainly appears that very short, whole-tree harvests should be avoided.

The model predictions should be viewed with caution. Actual numbers are only reported to indicate trends and compare alternatives. The model has not been validated against any long term experimental data. Hence, the precision and accuracy of the results are unknown.

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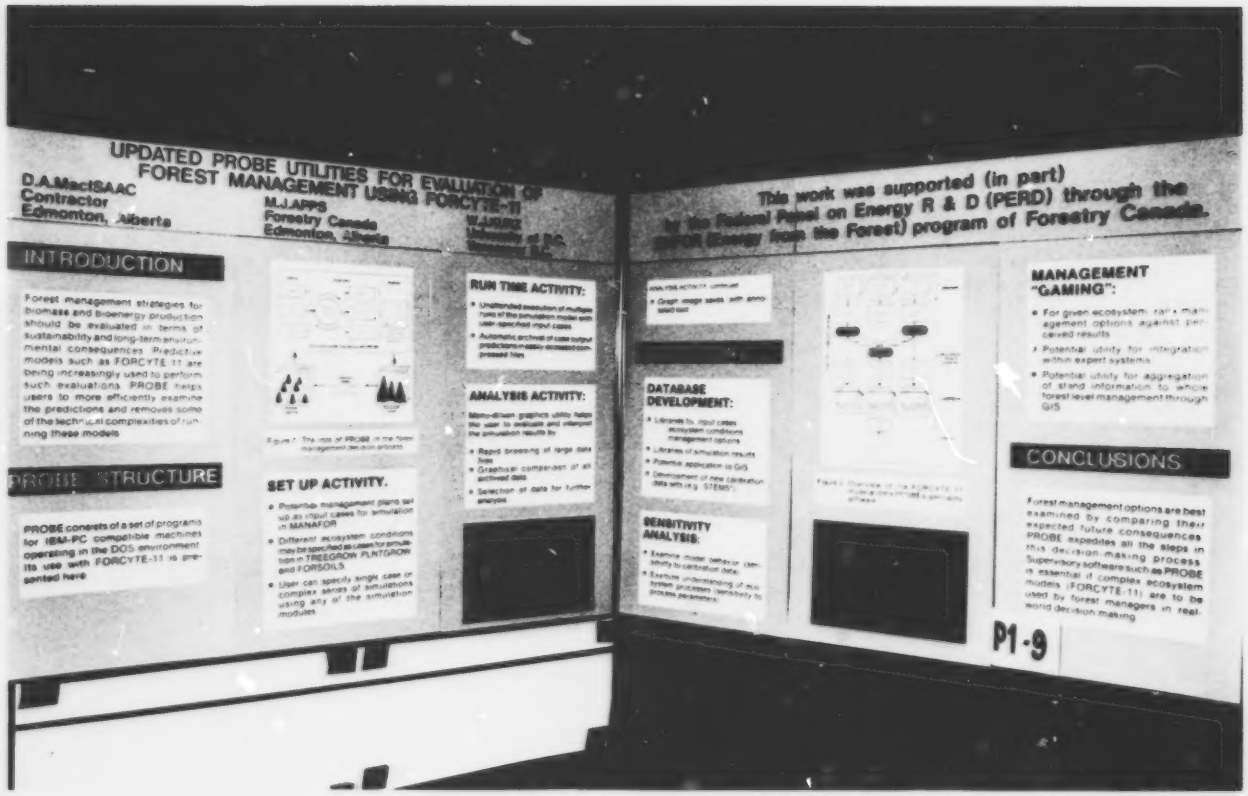
UPDATED PROBE UTILITIES FOR EVALUATION OF FOREST MANAGEMENT USING FORCYTE-11
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This work was supported (in part) by the Federal Panel on Energy R & D (PERD) through the ENFOR (Energy from the Forest) program of Forestry Canada.
INTRODUCTION
Forest management strategies for biomass and bioenergy production should be evaluated in terms of sustainability and long-term environmental consequences. Predictive models such as FORCYTE-11 are being increasingly used to perform such evaluations. PROBE helps users to more efficiently examine the predictions and removes some of the technical complexities of running these models.
PROBE STRUCTURE
PROBE consists of a set of programs for IBM-PC compatible machines operating in the DOS environment. Its use with FORCYTE-11 is presented here.
SET UP ACTIVITY.
Potential management plans set up as input cases for simulation in MANAFOR
Different ecosystem conditions may be specified as cases for simulation in TREEGROW PLNTGROW and FORSOILS
User can specify single case or complex series of simulations using any of the simulation modules
RUN TIME ACTIVITY:
Unattended execution of multiple runs of the simulation model with user-specified input cases
Automatic archival of case output predictions in easily accessed compressed files
ANALYSIS ACTIVITY:
Menu-driven graphics utility helps the user to evaluate and interpret the simulation results by
Rapid browsing of large data files
Graphical comparison of all archived data
Selection of data for further analysis
DATABASE DEVELOPMENT:
Libraries for input cases ecosystem conditions management options
Libraries of simulation results
Potential application to GIS
Development of new calibration data sets (e.g. STEMS)
SENSITIVITY ANALYSIS:
Examine model behavior (sensitivity to calibration data)
Examine understanding of ecosystem processes (sensitivity to process parameters)
MANAGEMENT "GAMING":
For given ecosystem, rank management options against perceived results
Potential utility for integration within expert systems
Potential utility for aggregation of stand information to whole forest level management through GIS
CONCLUSIONS
Forest management options are best examined by comparing their expected future consequences. PROBE expedites all the steps in this decision-making process. Supervisory software such as PROBE is essential if complex ecosystem models (FORCYTE-11) are to be used by forest managers in real-world decision making.
P1-9

UPDATED PROBE UTILITIES FOR EVALUATION OF FOREST MANAGEMENT USING FORCYTE-11

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The FORCYTE-11 forest yield and trend evaluator model is currently being tested with management gaming and sensitivity analysis. To allow users to more efficiently execute multiple model runs and handle the large amount of output data, a supervisory program (PROBE) has been developed. PROBE assists users during three activities: input data preparation, multiple run execution, and output data analysis. Since first reported at the 6th Bioenergy R&D seminar, the programs for the first two activities have been significantly improved to make them more user-friendly and efficient. In addition, an output data display and file manager has been developed to facilitate the analysis of model results with PROBE.

This output manager has several features which overcome limitations of the standard FORCYTE-11 output. Any output variable of any FORCYTE-11 module run (TREEGROW, PLNTGROW, FORSOILS, MANAFOR) can easily be selected and compared with other variables of the same or other module runs. The menu-driven environment provides both graphical and tabular display of data for comparison and analysis. Finally, several data storage and output options are available, including the ability to archive results in compressed, binary form.

Le modèle d'évaluation du rendement et des tendances des forêts FORCYTE-11 fait actuellement l'objet d'essais avec des programmes de jeux de gestion et des analyses de sensibilité. On a élaboré un programme superviseur (PROBE) afin de permettre aux utilisateurs d'exécuter efficacement plusieurs passages de modélisation et de manipuler les grandes quantités de données de sortie. Le programme PROBE aide les utilisateurs pendant trois types d'activités: la préparation des données, l'exécution de plusieurs passages et l'analyse des données de sortie. Depuis qu'ils ont été signalés pour la première fois au cours du 6e séminaire sur la R et D en bioénergie, les programmes pour les deux premières activités ont fait l'objet d'améliorations considérables qui les ont rendus plus conviviaux et plus efficaces. De plus, un programme de présentation des données de sortie et de gestion des fichiers a été éloboré en vue de faciliter l'analyse des résultats des modélisations avec le programme PROBE.

Le programme de gestion des données de sortie possède plusieurs caractéristiques qui lui permettent de surmonter les limitations imposées obtenues avec le modèle standard FORCYTE-11. Toute varable de sortie obtenue avec tout passage de module FORCYTE-11 (TREEGROW, PLNTGROW, FORSOILS, MANAFOR) peut être facilement choisie et comparée à d'autres variables du même passage ou d'autres passages du module. Le cadre du programme, qui est piloté par menus, permet de présenter les données sous forme graphique ou sous forme de tableaux afin de les comparer et de les analyser. Finalement, plusieurs options permettant de stocker et de restituer les données sont disponibles, dont la capacité d'archiver les résultats sous une forme binaire comprimée.

1 INTRODUCTION

As non-renewable energy sources are inevitably depleted, there is a need to develop renewable ones. Bioenergy, including forest fuels, is becoming more attractive as an alternative energy source, especially when the atmospheric impact of burning fossil fuels is considered.

Forest management strategies for the production of bioenergy have to be evaluated in terms of sustainability and long term environmental consequences. Because of the long time horizon of such evaluations, computer simulation models are appropriate assessment tools. FORCYTE-11 (Kimmins *et al.*, this volume) is an ecosystem simulation model, developed under the ENFOR (Energy from the Forest)

program of Forestry Canada to assess the environmental consequences of intensive forest management for the production of bioenergy.

As a trend evaluator, FORCYTE-11 is best suited for ranking and comparing different management options rather than relying on the absolute predictions. Currently, it is being tested on a variety of tree species (see Greval *et al.*, Sachs *et al.*, Pike and Meades, this volume). The use of FORCYTE-11 or other ecosystem models to evaluate forest management options requires multiple runs of the model with different initial conditions, management options or calibration parameters. As FORCYTE-11 moves from the development phase into the testing and validation phase, the complexity of setting up multiple module runs has increased greatly, as has the number of data and output files. The supervisor software package PROBE (Apps *et al.* 1988, Kurz *et al.* 1988) has been developed to manage FORCYTE-11 experiments which require a large number of simulation runs.

Since first reported at the 6th Bioenergy R&D Seminar (Kurz *et al.* 1988) PROBE has been enhanced. It now has expanded ability to set up, supervise, and analyze multiple FORCYTE-11 runs in a more user-friendly environment.

This paper describes the PROBE concept approach, and the utility of this approach to evaluating forest management practises with large ecosystem models. It also discusses improvements and new developments with PROBE. Although this paper deals explicitly with FORCYTE-11, the PROBE software can be adapted to work with other simulation models having a similar input/output structure (see Figure 1).

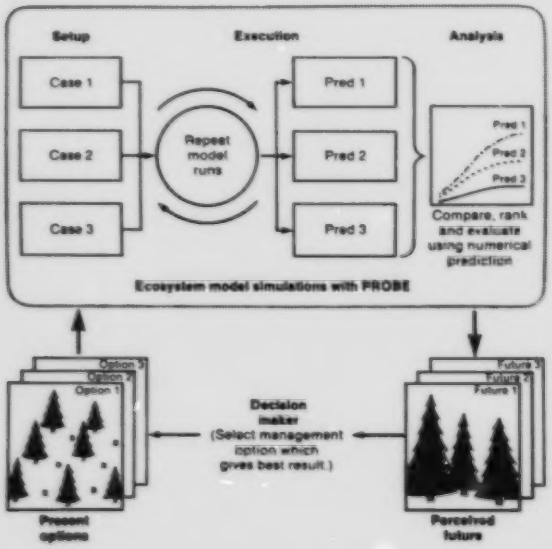

Figure 1: The role of PROBE in the forest management decision process.

2 PROBE CONCEPT

PROBE provides supervisory software which facilitates the use of FORCYTE-11 as a forest management analysis tool. It consists of several programs and associated files which help the user in preparing, executing, and analyzing FORCYTE-11 runs.

Figure 1 shows how PROBE operates within the forest management decision process. It acts as an interface between the user and the technical complexities of running the ecosystem model by providing data editing capabilities, unattended execution of multiple runs and automatic output file production and compression.

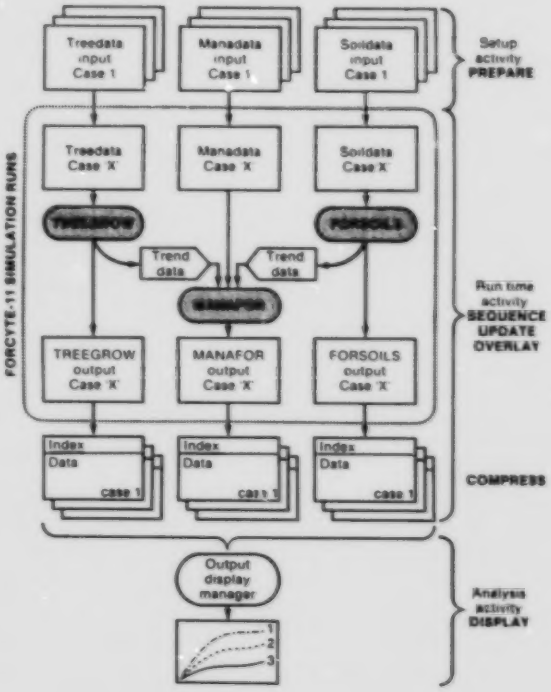

Figure 2: Overview of the FORCYTE-11 model and the PROBE supervisory software.

The PROBE software has features which enhance the operational capabilities of FORCYTE-11. For example, it can be used to set up single FORCYTE-11 run, a sequence of runs (an experiment), and sets of experiments. More importantly, it makes the output results more readily accessible for analysis and interpretation. It allows the user to graph one variable against another while browsing the data and checking for correlations. It also facilitates the selection of data for statistical analysis and graphical or tabular presentation by software external to PROBE.

3 PROBE STRUCTURE AND PROGRAMS

The function of PROBE can be divided into three main activities: data set up, program execution, and data analysis. Each activity is facilitated by specific programs, some of which are activated individually while others are run automatically as part of the execution sequence. These programs, written in Turbo Pascal, are running on IBM-PC compatible machines under the DOS environment.

While the original concept remains the same, there have been significant changes to several PROBE program modules. The following sections summarize improvements since originally reported. More technical descriptions are given in the appropriate user's manuals (Kurz and Apps (1988), MacIsaac and Apps (1989)).

3.1 Set Up Activity

The most important changes to the data set up activity have been extensive modifications and improvements to the interactive program PREPARE (previously called SETUP), which helps the user in the tasks needed to set up multiple FORCYTE-11 runs managed by PROBE.

Using PREPARE, the user can define specific data changes (case overlays) to the original data set (default input files) needed for each program module run. As discussed below in the section on applications, this now allows users to create a database of input options. While preparing the overlays, the original default data files can be displayed for reference and editing; in addition, previously defined case overlays can be edited. Figure 2 is a simplified overview of the FORCYTE-11 model and the PROBE supervisory software and shows how data cases are used as input to FORCYTE-11 program modules. The case descriptions are stored, and at execution time are used as overlays to modify the input data files. With PREPARE, the user can also attach a header section with comments for each output file.

3.2 Run Time Activity

PROBE controls the execution of the FORCYTE-11 program modules and the production of output data files. This process has been significantly improved through the modification of the program SEQUENCE and the addition of the program COMPRESS.

SEQUENCE has been changed to permit the execution of a single FORCYTE-11 program module run (Figure 2), a user-defined sequence of runs (called an experiment) or a set of experiments. The execution sequence is defined in a file which controls the order in which the FORCYTE-11 program modules are run. The file also designates the specific input data file overlay (case) which will be used for input to the specific module. This allows the user to set up an unattended execution of one or more sequences of runs.

Each FORCYTE-11 module produces one or more output files containing simulation results. The available output formats are: tabular summary tables, diagnostic graphs (line printer plots and

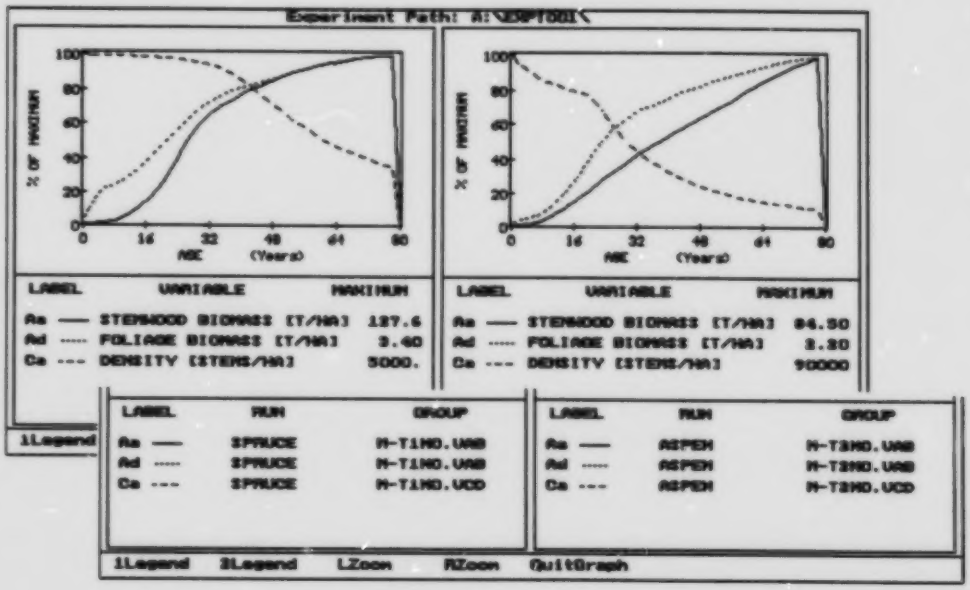

Figure 3: Screen image from program DISPLAY, showing customized output from two FORCYTE-11 runs. The second "pop-up" legend has been superimposed on the first

numerical ASCII files), and numerical ASCII spreadsheet files. However, the FORCYTE-11 output control is "all or nothing", and does not permit selective suppression of output. The output files generated during multiple runs can require large amounts of disk storage space. Furthermore, a direct comparison of variables located in different output files (even of the same format) is not readily possible.

COMPRESS, the second major PROBE program involved in the execution of FORCYTE-11 runs, overcomes the limitations mentioned above. It converts the standard FORCYTE-11 output data to a form which significantly reduces the storage requirements (up to 75%), while permitting faster and more flexible access to it. It performs this magic by converting the regular FORCYTE-11 output into two new files: a small index file which identifies the location of data in the second, binary file. The compressed files have been structured to make them suitable for further data analysis.

3.3 Analysis Activity

The most extensive changes to PROBE have been in support of data analysis. While the graphical display and analysis using the spreadsheet program Symphony (Lotus Development Corp.) was useful for prototype development, its associated computer overhead and relative inflexibility make it unsuitable for use with the greatly expanded data sets provided by the COMPRESS utility. It has been replaced with DISPLAY.

DISPLAY is an interactive program which uses menus and "point-and-pick" routines to efficiently retrieve and analyze the FORCYTE-11 output data. DISPLAY loads the index file information produced by COMPRESS from a user- selected subset of FORCYTE-11 output. It then allows the user to easily and quickly choose, graphically display, and browse through any combination of variables from FORCYTE-11 module runs (TREEGROW, PLNTGROW, FORSOILS, MANAFOR) (Figure 3).

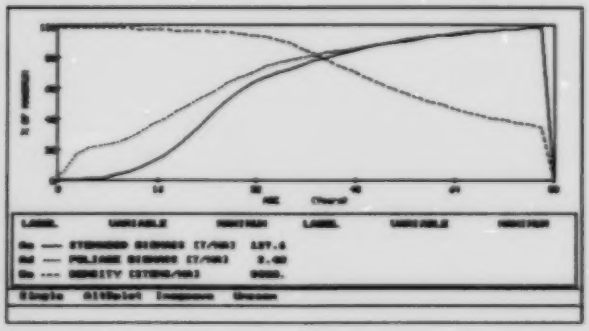

Figure 4: Screen image from program DISPLAY, showing customized zoom graph. The user can also "page through" one plot at a time.

After selecting output for analysis, the user can "page" through several output graphs or "zoom in" on specific graphs (Figure 4), and can also define the combination of variables shown in any graph display. DISPLAY has been designed to show dynamic trends (variables *vs.* time) or to plot relationships between variables (e.g., stand density (stems/ha) *vs.* foliage biomass (t/ha)). It also permits numerical manipulation of the data, for example, changing scaling factors. Once they are displayed, selected graphs can be printed or stored with user annotation for later retrieval.

DISPLAY greatly enhances the usefulness of the original FORCYTE-11 output. As well, this new data display and analysis manager can act as a selector for data to be exported to commercial software such as spreadsheet programs, statistical packages, database systems, and presentation graphics.

4 APPLICATIONS

As illustrated in Figure 1, PROBE provides the flexibility required for a useful decision support tool for forest managers. Although initially designed for use with the FORCYTE series of ecosystem models, PROBE has application as a multiple run management tool for other predictive models. The specific applications of PROBE to FORCYTE-11 are discussed below.

4.1 Database Development and Management

In FORCYTE-11, the initial ecosystem conditions and the forest management activities are defined in input data files. With PROBE, the user can assemble libraries of different ecosystems and management options. For example, nine different management regimes may represent the combination of three levels of fertilization each with three levels of thinning. Using the PROBE program PREPARE, the user defines a file with the default management options and then specifies how each of the nine management regimes (cases 1-9) differs from the default data files. In future simulation runs, each management regime can be referenced simply by its case number, rather than reassembling the desired data each time. Similarly, different initial ecosystem states can be pre-established. There is no limit to the number of cases that can be defined in such libraries of management options or ecosystem conditions.

Because PROBE also manages the output from FORCYTE-11 runs, it can be used to develop libraries of the ecosystem simulation results. These describe ecosystem responses (e.g., growth curves) to different management options.

4.2 Sensitivity Analysis and Management Gaming

Other practical applications for PROBE include sensitivity analysis and management gaming. Sensitivity analysis investigates the response of the forest ecosystem simulation to changes in various input parameters (as in Apps *et al.* 1988). Management gaming may be regarded as a subset of such analysis, in which the run conditions are

specified by management scenarios (see Figure 1). Such analyses often require large numbers of runs. PROBE is being used to prepare and run a factorial simulation experiment with Balsam fir in Newfoundland (Pike and Meades, this volume) with 96 sets of output data: 2 harvest intensities X 4 thinning regimes X 4 fertilization rates X 3 rotation periods. PROBE allows the user to conduct such a large experiment with minimum effort. The data produced by such an experiment are easily compared using DISPLAY. By developing a management options database with PREPARE, the user does not have to run the whole experiment at once. Initial runs can be selected to test various management options, and changes to the data can be made before the main run is executed.

4.3 Evaluating Input Data Requirements

STEMS* is being tested as an input data generator for FORCYTE-11 (Grewal *et al.* this volume). Multiple runs are needed to evaluate the output from STEMS* developed with different biomass equations and PROBE is used to facilitate this analysis. The STEMS* data are incorporated with the FORCYTE-11 input files using data case overlays. DISPLAY allows output from different runs to be compared graphically (Figures 3 and 4).

4.4 Future Directions

A future direction may be to integrate PROBE into an Artificial Intelligence (AI) shell. One approach would be a three tier structure in which ecosystem simulation is performed with FORCYTE-11 or other forest ecosystem model. PROBE would be at the next level, and would set up data cases and manage the multiple runs. At the highest level would be an AI "inference engine" which would help the user organize and query the simulation results which form part of the knowledge base.

As mentioned previously, PROBE can be used to generate a library of ecosystem responses such as growth curves. This may help FORCYTE-11 tie into regional forestry models by allowing the aggregation of stand information to provide whole forest predictions within a GIS framework. COMPRESS provides the proper storage technique; DISPLAY is the tool by which output is assembled and analyzed. DISPLAY utilities could be used to transfer selected data to attribute files for integration with GIS models and regional forestry.

5 CONCLUSIONS

Forest managers are increasingly trying to avoid long-term environmental degradation of forest ecosystems while optimizing returns on their management effort. Various forest management options are best examined by comparing their expected future consequences using a predictive forest simulation model. This task involves setting up the model for a number of different conditions, executing the model for these conditions, generating the appropriate output and, finally, ranking and evaluating the simulated future ecosystem based on the perceived benefit of each. The strength of PROBE is that it supervises and expedites all the steps in this decision-making process. It also provides a framework for integrating large simulation models in other decision support tools such as GIS and AI.

Supervisory software such as PROBE becomes essential if complex ecosystem models like FORCYTE-11 are to be used by forest managers in real-world decision making.

ACKNOWLEDGEMENTS

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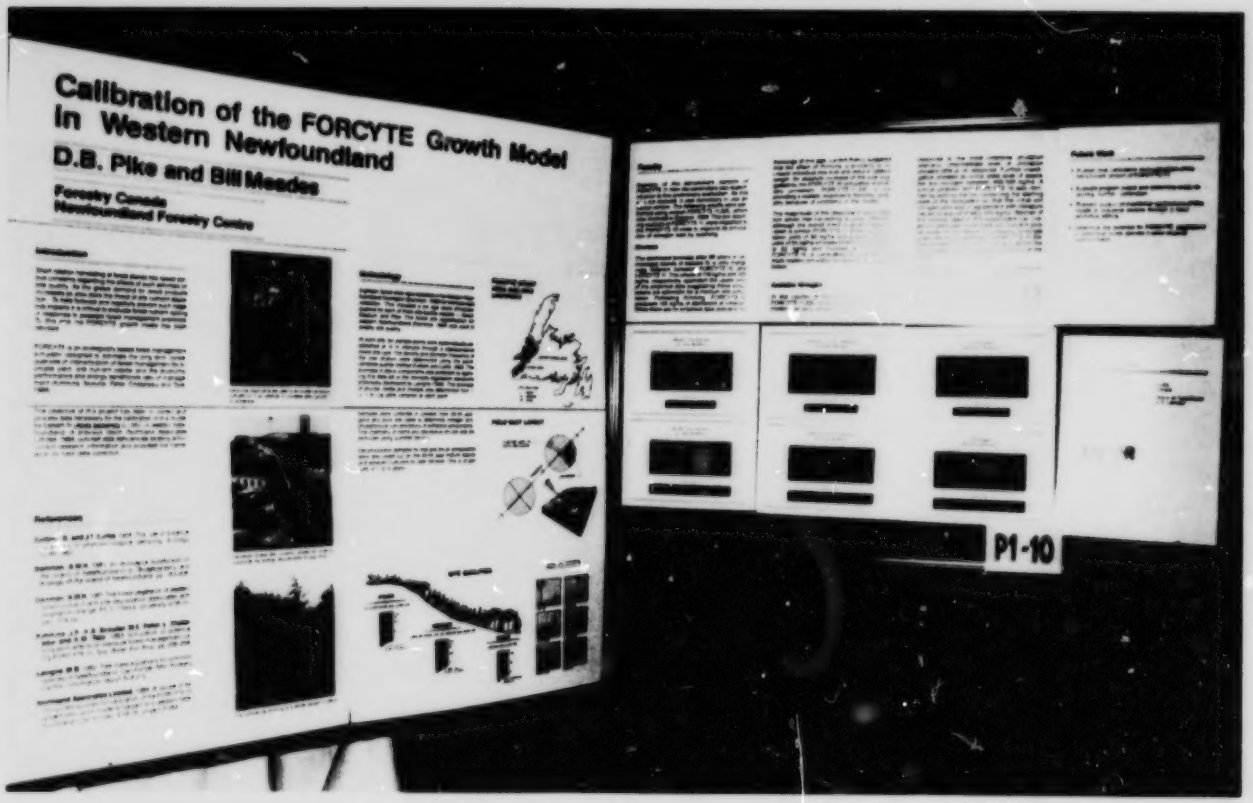
Calibration of the FORCYTE Growth Model
in Western Newfoundland
D.B. Pike and Bill Meades
Forestry Canada
Newfoundland Forestry Centre
P1-10

A PRELIMINARY EVALUATION OF FORCYTE-11 USING WESTERN NEWFOUNDLAND BALSAM FIR STANDS

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FORCYTE-11 is being calibrated and evaluated for balsam fir in the Western Newfoundland ecoregion. FORCYTE (FORest Nutrient Cycling and Yield Trend Evaluator) is a complex ecosystem simulation model. Empirical data, supplied by previous ENFOR contracts, has been processed and input into appropriate data sets. A literature review, to supplement data requirements not yet realized through calibration field work, is ongoing. All data inputs have been documented. A simulated factorial experiment was conducted to provide an evaluation of the model's response to thinning and fertilization. A comparison of this experiment with the results from a similar experiment using FORCYTE-10 is provided. Results are compared with available data from the literature and field experiments in the area.

On procède actuellement à l'étalonnage et à l'évaluation du modèle FORCYTE-11 en vue de l'appliquer à des sapins baumiers dans l'écorégion correspondant au secteur ouest de Terre-Neuve. Le modèle FORCYTE-11 (FORest Nutrient Cycling and Yield Trend Evaluator) est un modèle permettant de simuler des écosystèmes d'importance. Des données empiriques, obtenues au cours de contrats réalisés dans le cadre du programme ENFOR, ont été traitées et entrées dans les ensembles appropriés de données. On procède actuellement à une étude de la littérature, en vue de venir compléter les exigences en matière de donnés qui n'ont pas encore été rélisées pendent les travaux d'étalonnage sur le terrain. Toutes les entrées ont été documentées. Une simulation factorielle a été réalisée en vue d'évaluer la réponse du modèle à l'éclaircie et à la fertilisation. On compare les résultats de cette expérience avec les résultats d'une expérience semblable réalisée avec le modèle FORCYTE-10. On compare les resultats obtenus avec les données disponibles publiées dans la littérature et celles obtenues au cours d'expériences sur le terrain dans la région.

INTRODUCTION

FORCYTE (FORest Nutrient Cycling and Yield Trend Evaluator) is an ecosystem modelling framework being developed for Forestry Canada under ENFOR contracts to Dr. J.P. Kimmins of the University of British Columbia. It attempts to predict the consequences associated with different land management practices for biomass production and site nutrient capital. The model relies on nutrient limitation as the primary regulator of biomass production. FORCYTE-11 also simulates interactions between light, stand canopy structure and the resulting photosynthetic responses (Kimmins and Scoullar, 1987).

History of ENFOR Project P-264

FORCYTE, being a "hybrid" model, requires empirical data as input for its process simulation modules (FORSOILS, TREEGROW, PLNTGROW). The resulting output is used to drive the ecosystem management module (MANAFOR).

ENFOR Project P-264 (Calibration of FORCYTE Simulation Model for Newfoundland Forest types) was initiated in 1984. Northland Associates Limited were contracted to collect the empirical data necessary for calibrating the model for balsam fir forests in the Western Newfoundland ecoregion. The primary objective was to provide estimates of biomass and nutrient concentrations for tree, shrub and herb components, stand densities, and litter and humus decomposition rates. A total of 18 sites were sampled (i.e. three site qualities were sampled over a chronosequence of six age classes). Site qualities were selected using Damman forest types (Damman, 1967) as an indication of the site's position on an edaphic nutrient gradient. A description of the data collected and methods used is presented in Moore and Meades (1988). Additional sampling was required in subsequent years to follow up on previously established decomposition experiments and to refine the calibration data base.

In 1986 FORCYTE-10 was successfully installed on the Newfoundland & Labrador Region's VAX 8200 minicomputer and the empirical data collected was entered into the appropriate data sets. Results of FORCYTE-10 calibration and simulation were reported by Meades (1986).

Shortly after FORCYTE-11 became available and was also installed. With the advent of the IBM PC standard for microcomputers, it was decided to port the model to a microcomputer environment. Given the size and structure of the FORCYTE-11 source code, the absence of the current 80386 microprocessor and software which made optimum use of 80286 microprocessor, it was necessary to use a coprocessor board for program execution on a PC. The 32 bit Definicon DSI-32 coprocessor board was selected to perform this.

Once installed on the microcomputer, preliminary testing was initiated. Early evaluation proved difficult to perform as the model was still in developmental stages, and still is at the time of this paper. This exercise isolated areas where the model was functioning improperly and through communications with the developers some of the problems were rectified.

Data collected by Northlands Associated Limited (1985) was processed to be in a form acceptable for input into the model. A series of programs were developed to determine density and frequency distributions of the sample stands. Using the output from these programs and the component biomass regression equation developed by Lavigne (1982), component biomass values were calculated for each of the stands.

Required inputs which could not be empirically calibrated due to temporal or financial constraints were taken from various literature sources. As far as possible data was only taken from regions having a climate and vegetation similar to Western Newfoundland to maintain, at least, the "spirit" of empirical calibration. Subalpine balsam fir stands in New Hampshire (Lambert et al., 1980) and New York (Sprugel, 1984) were particularly useful in this respect. An ongoing literature search is maintained to improve the calibration data and to provide a background to check the results of the various simulations.

METHODS

Delivery of the benchmark version of FORCYTE-11 from the contractors was expected prior to this preliminary evaluation. As this was not realized it was necessary to use an earlier version. The following results were performed using version FORCYTE-11.33C, which was received in October 1988. The soil leaching routines of FORCYTE-11 were imported to the FORCYTE-10 code to improve its simulation of nitrogen loss by leaching.

The FORCYTE-10 users manual (Kimmins and Scoullar, 1983) suggests that the optimum use of FORCYTE is in conducting factorial experiments to examine the consequences of varying the value of one or more management options and provides an example of a possible simulation experiment. This example was used as the basis of the following experiment. It provides a simulation of management practices currently being conducted on an experimental and operational level in balsam fir forests of Western Newfoundland.

A 3 x 2 x 4 x 4 design was used and dealt with the following factors:

1) Three rotation lengths
   - R1 - 30 years
   - R2 - 60 years
   - R3 - 90 years
2) Two utilization levels
   - U1 - Stems only harvest
   - U2 - Whole tree harvest
3) Four thinning levels
   - T1 - No thinning
   - T2 - Light thinning (to 4000 stems/ha)
   - T3 - Medium thinning (to 2500 stems/ha)
   - T4 - Heavy thinning (to 1000 stems/ha)

4) Four fertilization levels
   F1 - No fertilization
   F2 - Light fertilization (100 kgN/ha)
   F3 - Medium fertilization (200 kgN/ha)
   F4 - Heavy fertilization (400 kgN/ha)

Runs were performed using the PROBE data management software (Kurz et al.) and analysed using the Output Display Manager (Apps and MacIsaac, in prep.), which is currently under development.

Due to the problems discussed below, a full reporting on the results of the factorial analysis was not warranted at this time. Only a few select examples are used to demonstrate problems with the FORCYTE-11.33C version.

RESULTS

Biomass

The stemwood biomass after 60 years in unmanaged stands of balsam fir is only marginally different between FORCYTE-10 and FORCYTE-11 (Figure 1). The values of 119 kg/ha and 105 kg/ha, respectively, approach the upper limit of the empirical data suggesting these simulations are optimistic for a medium site simulation. Following thinning, FORCYTE-10 produces 135 kg/ha of stemwood at rotation (Figure 2). While there are no empirical data available for thinnings of this age, current theory suggests that the effect of thinning is primarily to increase individual tree size and reduce rotation length. An absolute increase of the size suggested by the FORCYTE-10 simulation is probably unrealistic. FORCYTE-11.33C is not providing a realistic response to thinning, probably because of problems in the model.

The magnitude of the response to short rotation whole tree harvesting is quite different, although the overall trend in growth deterioration is similar (Figure 3). FORCYTE-11 shows a first rotation yield of 80 kg/ha and a sixth rotation yield of 65 kg/ha whereas FORCYTE-10 starts at 82 kg/ha and finished at 17 kg/ha. FORCYTE-10 is considered to provide the more realistic simulation for reasons discussed below.

Available Nitrogen

In the course of factorial experiments on FORCYTE-11.33C, it became apparent that the model was only showing significant growth response to the most intensive utilization scenario. Intermediate levels of utilization showed little or no response. Further investigation showed an initial state level of available soil nitrogen between 400-500 kg/ha (Figures 4-6). A similar problem with FORCYTE-10 was rectified by editing the file containing the starting state of the ecosystem so that the initial soil nitrogen pool was in agreement with literature values of approximately 200 kg/ha. Neither of the models used in this experiment can create an adequate initial state soil nutrient pool because of the failure to properly simulate quantities of soil leaching. In FORCYTE-11.33C this limitation is due to the nature in which the soil nitrogen carrying capacity (SNCC) of the organic fraction is calculated:

$$\text{SNCC (Organic)} = \text{Max Humus N Retention (kg/T)} \times (\text{Humus (T/ha)} + \text{Litter (T/ha)})$$

This results in a gross over-estimate of the upper limit of the available nitrogen pool and low levels of nitrogen leaching, leading to luxury consumption and growth limited only by the upper limit imposed by the empirical data.

DISCUSSION

Future Work

Following delivery of the benchmark version of FORCYTE-11, it will be subjected to intensive evaluation with respect to its application to forest management in Western Newfoundland.

Results of the calibration evaluation will be documented in Forestry Canada ENFOR information reports.

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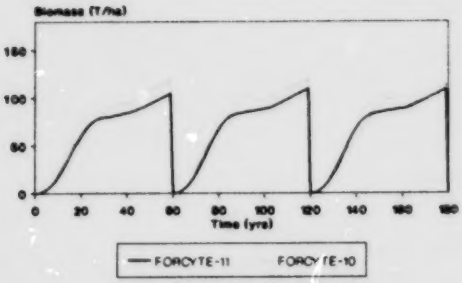


Figure 1. Stemwood biomass (T/ha) of an unmanaged fir stand over a 80 year rotation & conventional harvest.

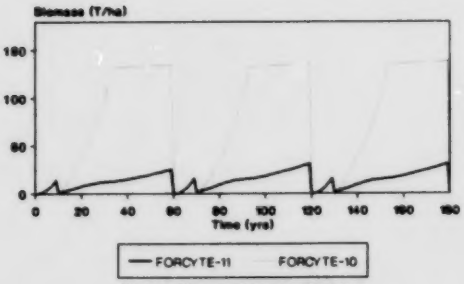


Figure 2. Stemwood biomass (T/ha) in a fir stand thinned to 2500 stems/ha, 60 year rotation & conventional harvest.

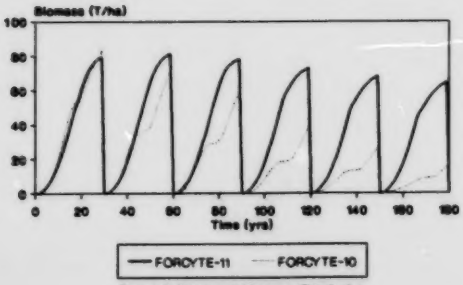


Figure 3. Stemwood biomass (T/ha) of a fir stand following a 30 year rotation & a whole tree harvest.

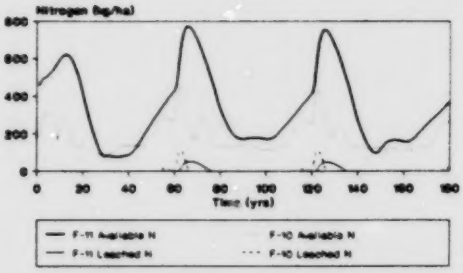


Figure 5. Available and leached nitrogen of an unmanaged fir stand over a 60 year rotation & conventional harvest.

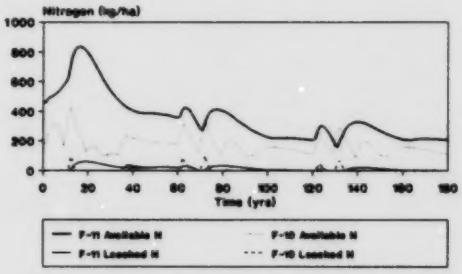


Figure 5. Available and leached nitrogen in a fir stand thinned to 2500 stems/ha, 60 year rotation & conventional harvest.

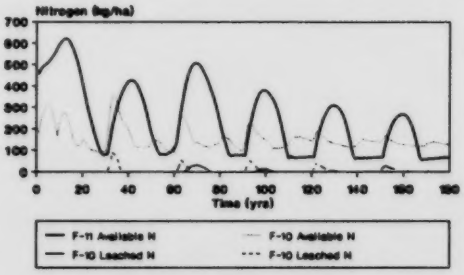
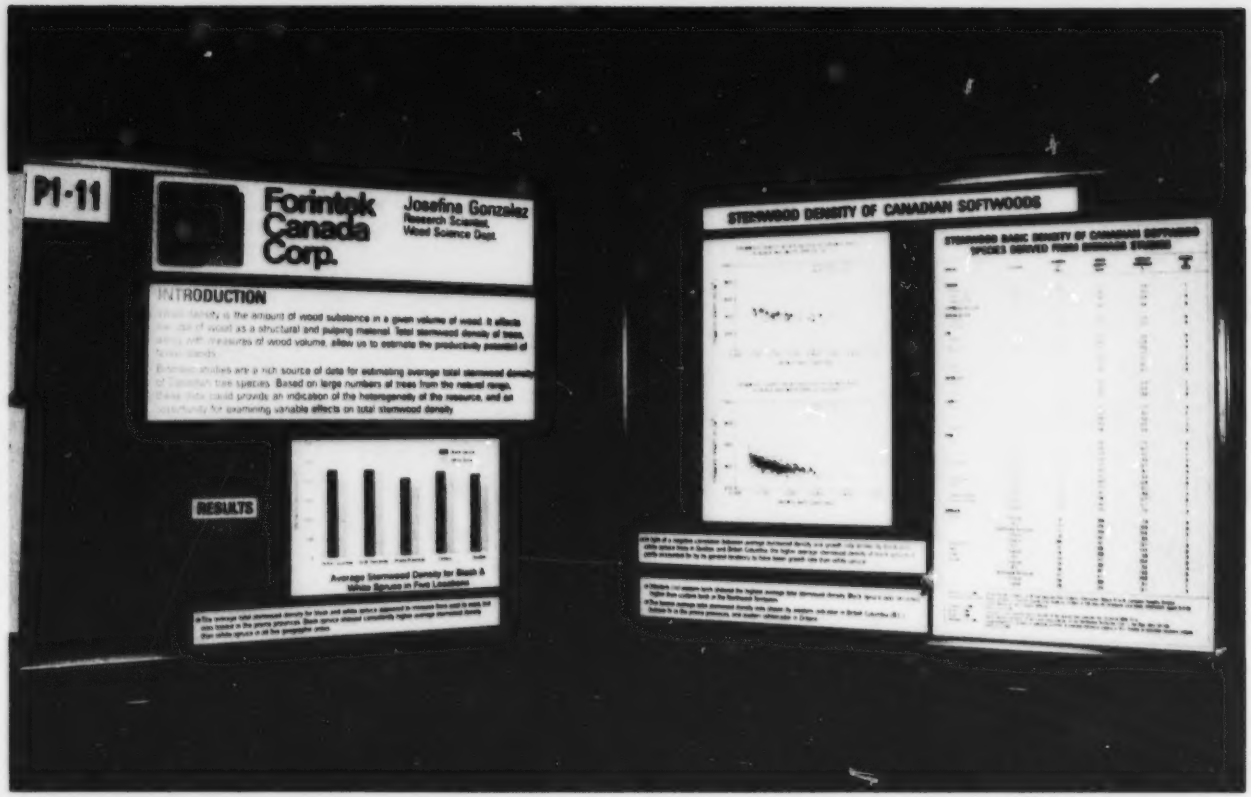


Figure 6. Available and leached nitrogen of a fir stand following a 30 year rotation & a whole tree harvest.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Forintek Canada Corp.
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Wood Science Dept.
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STEMWOOD DENSITY OF CANADIAN SOFTWOODS

AVERAGE STEMWOOD DENSITY OF CANADIAN TREE SPECIES DERIVED FROM BIOMASS STUDIES

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Review of the literature showed that different sampling and analytical techniques were used to obtain average stemwood density of Canadian tree species. To minimize the effect of such variables, average stemwood densities of Canadian softwood species presented in this paper are derived from and limited to biomass studies in which total stemwood was analyzed and trees were selected from the natural range of the species. Larch (eastern and western species) gave the highest stemwood density while eastern white and western red cedar gave the lowest. Density variation in the average stemwood density of black and white spruce in five locations are presented.

Une étude de la littérature a révélé qu'on outilisait différentes méthodes d'échantillonnage et d'analyse pour déterminer la densité moyenne du bois de fût d'espèces canadiennes d'arbre. Afin de réduire au minimum l'effet de tels variables, les densités moyennes due bois de fût d'espèces canadiennes de conifères, qui sont presentées dans cette communication, sont tirées uniquement d'études sur la biomasse dans lesquelles tout le bois de fût était analysé et les arbres provenaient de l'aire naturelle des espèces en question. Ce sont les mélèzes (espèces de l'est et de l'ouest) qui possédaient le bois de fût le plus dense, tandis que le cèdre blanc et le cèdre rouge possédaient la densité la plus faible. On donne la variation de densité moyenne du bois de fût de l'épinette noire et de l'épinette blanche à cinq endroits.

INTRODUCTION

Wood density is the amount of wood substance in a given volume of wood. It affects the use of wood as a structural and pulping material (2,5,16) and is usually a good indicator of its suitability for other uses.

Estimates of average wood density for Canadian species in the natural range have been based on different methods. The survey reports of Jessome (7) and Smith (14) were based on samples taken from randomly selected logs or planks in the mills. Kennedy and Swann (9) calculated whole-tree relative density using equations relating breast-height core to whole tree density. Sampling at mills precludes estimates of variation in the average stemwood density of a species. Average tree density values reported by Kennedy and Swann were based on relationships established for trees grown in the United States.

In recent years, several biomass studies have been conducted on Canadian tree species across the country (1,11,12,13,15). These studies have collected measurements which allow estimates of volume-weighted average stemwood density of trees. The studies are usually based on a large number of trees from the natural range of a species. Thus, they could provide an indication of the heterogeneity of the resource, and an opportunity for examining trends in stemwood density of species.

This report presents average stemwood density of Canadian softwood species collated from four biomass studies (1,8,12,13); estimates of average stemwood density for species in British Columbia and Quebec using raw data provided by the project leaders of two separate studies (11,15); and average stemwood density trends for black and white spruce as a function of growth rate.

MATERIALS AND METHODS

Raw data provided by the authors of two separate biomass studies (11,15) made it possible to calculate average stemwood density for softwood species in British Columbia (B.C.) and Quebec. The methods of sampling and density measurement used have been described (11,15).

For the purpose of the present report, volume-weighted average stemwood density for each tree, and the overall average for the species were calculated. In the case of the Quebec trees, stem volume was corrected for bark volume which was estimated by dividing the weight of the bark by its density. Bark density values reported in the literature (6,10) were used. In addition, stemwood density reported for trees from the Northwest Territories, the prairie provinces, and Ontario were collated from four biomass studies (1,8,12,13). The additional data provided an opportunity to examine trends in average stemwood density of species from different geographic areas. This was illustrated for black and white spruce which are widely distributed across Canada.

Average stemwood density for black and white spruce trees were plotted as a function of their growth rates (diameter at breast height/tree age). This was done only for the B.C. and Quebec trees for which data were available for carrying out this analysis.

RESULTS

The average stemwood density and the coefficients of variation for the Canadian softwood species examined are presented in Table 1. Both western and eastern larch showed the highest average total stemwood density. Black spruce was recorded higher than eastern larch in the Northwest Territories. The lowest average total stemwood density was shown by western red cedar in B.C., balsam fir in the prairie provinces, and by eastern white cedar in Ontario. This ranking was borne out by data reported by Jessome (7) and Smith (14) although the average values they reported were different. This is likely due to the difference in the method of sampling used.

The average total stemwood density of black and white spruce seemed to increase

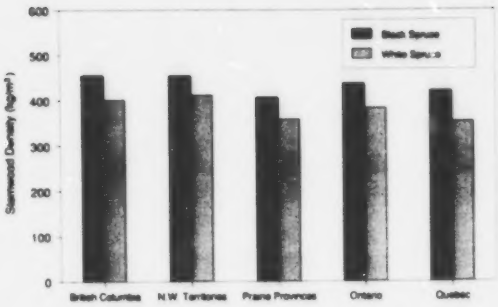

Fig. 1. Average Stemwood Density for Black & White Spruce in Five Locations

from east to west, but was lowest in the prairie provinces (Figure 1). It is interesting to note that a similar trend for black spruce breast-height density was observed across Alaska (3).

Black spruce appeared to give higher average stemwood density than white spruce. No statistical analysis was carried out to test if this difference is significant. Nonetheless, the trend appeared to be consistent in all five geographic areas.

In an attempt to explain the higher density of black spruce, stemwood density was plotted as a function of growth rate (the ratio of diameter at breast height to age) for black and white spruce in B.C. and Quebec, for which data were available for carrying out the analysis. This was prompted by an earlier study (4) that suggested a negative correlation existed between wood density and growth rate for white spruce.

The plots are shown in figures 2 and 3. Second-order equations show that the relationship between stemwood density and growth rate in black and white spruce is negative and significant ($p > 0.01$). The relationships for black and white spruce are slightly different for Quebec and B.C. In B.C., it would appear that the plots for black and white spruce practically fall on the same curve, but majority of the black spruce trees are on the low-growth portion of the curve while majority of the white spruce trees are on the

Table 1

STEMWOOD BASIC DENSITY OF CANADIAN SOFTWOOD SPECIES DERIVED FROM BIOMASS STUDIES

SPECIES	LOCATION	NUMBER OF TREES	WOOD DENSITY kg/m³	COEFF OF VARIATION %	SOURCE OF DATA
CEDAR					
Eastern White	Ontario	66	311	7.4	1
Eastern Red	Ontario	16	437	5.3	1
Western Red	B.C.	65	342	13.6	6
CYPRESS, YELLOW	B.C.	33	443	15.6	6
DOUGLAS-FIR					
Interior	B.C.	35	440	11.4	6
Coastal		42	421	12.0	6
FIR					
Alpine	B.C.	82	362	12.4	6
	Alberta	60	361	12.8	4
Balsam	Prairies	60	332	10.0	4
	Ontario	17	341	6.7	1
	Quebec	141	348	17.1	3
Grand	B.C.	36	359	15.3	6
Pacific Silver	B.C.	42	386	14.7	6
HEMLOCK					
Eastern	Ontario	122	406	11.3	1
	Quebec	68	389	12.9	3
Western	B.C.	59	436	13.8	6
LARCH					
Eastern	Prairies	60	471	7.7	4
	Northwest Territories	56	440	8.0	5
	Ontario	60	494	6.3	1
	Quebec	73	454	10.5	3
Western	B.C.	35	506	12.9	6
PINE					
Jack	Prairies	60	408	7.5	4
	Northwest Territories	56	408	10.7	5
	Ontario	69	418	6.2	1
	Quebec	109	404	9.9	3
Lodgepole	B.C.	76	425	12.7	6
	Alberta	60	393	8.1	4
	Alberta	85	424	6.9	2
Ponderosa	B.C.	38	405	12.8	6
Red	Ontario	94	372	12.1	1
	Quebec	39	381	8.0	3
Western White	B.C.	39	398	12.7	6
Eastern White	Ontario	128	342	11.1	1
	Quebec	43	376	7.5	3
SPRUCE					
Black	Prairies	58	404	7.4	4
	B.C.	55	455	10.9	6
	Northwest Territories	51	454	10.6	5
	Ontario	39	437	8.5	1
	Quebec	568	421	12.7	3
Engelmann	B.C.	41	403	13.0	6
Red	Quebec	50	380	9.6	3
Sitka	B.C.	34	412	15.4	6
White	Prairies	59	360	9.2	4
	B.C.	94	401	12.6	6
	Northwest Territories	61	411	15.0	5
	Ontario	56	383	9.1	1
	Quebec	56	353	12.1	3

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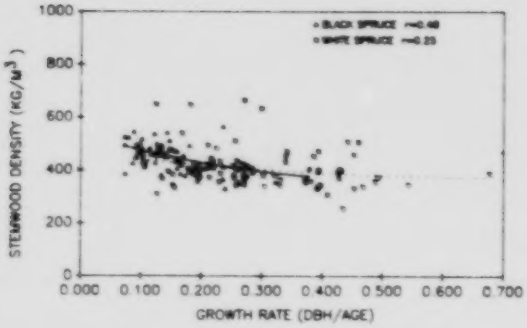

Fig. 2. Stemwood Density As A Function of Growth Rate in Black and White Spruce (B.C.)

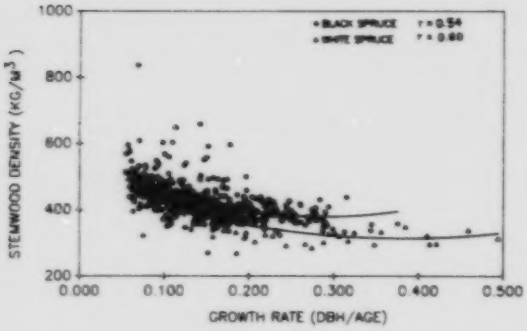

Fig. 3. Stemwood Density As A Function of Growth Rate in Black and White Spruce (Quebec)

higher growth rate. Because the r-value for these relationships is low, growth rate differences could only partly explain the higher density in black spruce in B.C.

The picture in Quebec is slightly different. Again, as in B.C., majority of the black spruce trees had lower growth rate than white spruce, but it would appear that even at the same growth rate, black spruce showed higher stemwood density than white spruce. This is more easily obvious in the growth rate region between 0.2 and 0.3 cm per year, where most of the black spruce showed higher stemwood density than the white spruce trees. It would seem that in Quebec, growth rate could partly account for differences in density within black or white spruce, but not differences between them.

CONCLUSIONS

Biomass studies, which are usually designed to quantify existing forest resource materials, are a rich source of data for estimating volume-weighted average stemwood density of various Canadian species. Because these studies measure characteristics of a large number of trees from the natural range, they could give an indication of the heterogeneity of the resource, and provide opportunities for examining relationships between these characteristics and stemwood density.

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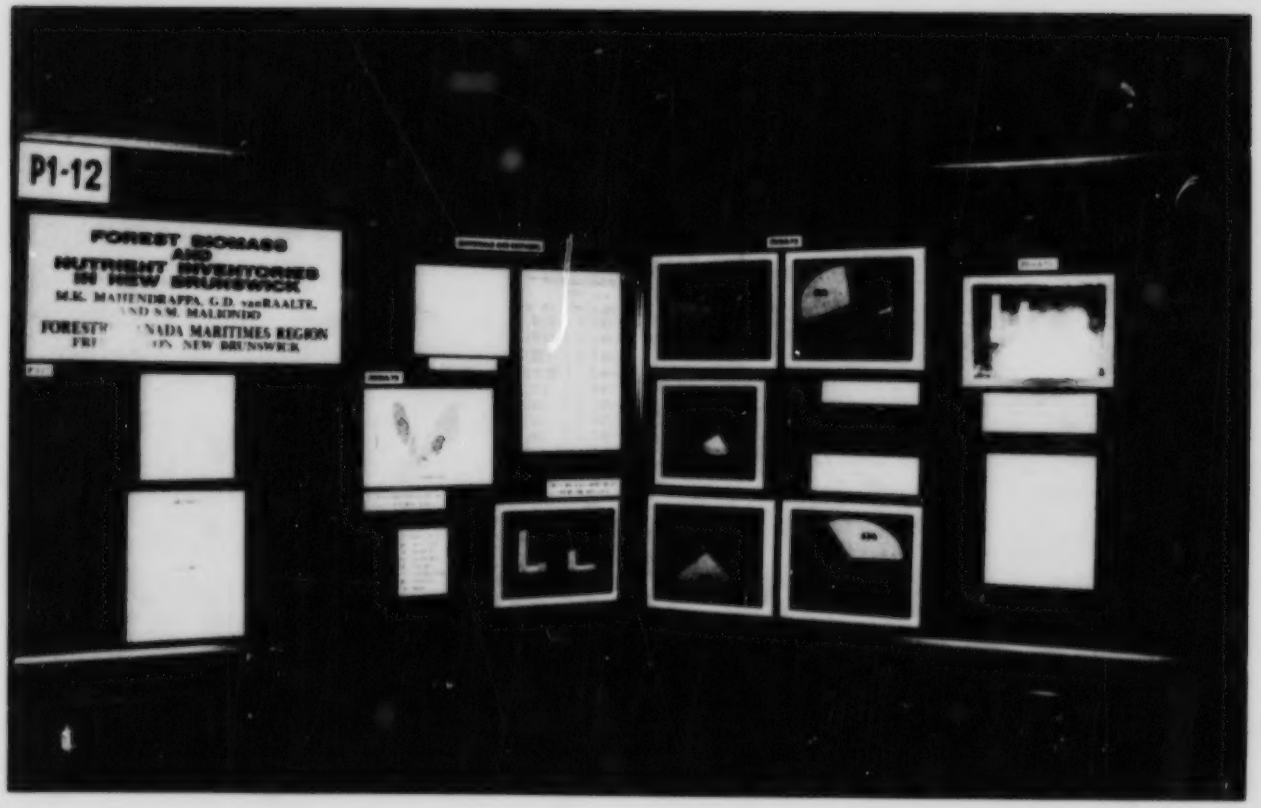
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FOREST BIOMASS
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FOREST BIOMASS AND NUTRIENT INVENTORIES IN NEW BRUNSWICK

Mahendrappa, M.K., G. D. Van Raalte and S. M. Maliondo

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ABSTRACT

In New Brunswick commercially important tree species growing on good, medium and poor sites were characterized in terms of their above ground biomass and nutrients in their components and in the below ground portions of stands. The data are essential and useful in evaluating importance of site classes for considerations such as possible energy from biomass; environmental impacts of biomass utilization for energy; establishment of monoculture plantations and so on.

RESUMÉ

Au Nouveau-Brunswick les principales essences commerciales sur des sites considérés bons, moyens et pauvres, one été caractérisées selon la biomasse et les éléments nutritifs que contienment les peuplements en surface et dans leurs parties souterraines. Les données sont utiles et même essentielles à l'évaluation de l'importance des classes de fertilité pour fins protiquer telles que l'utilisation possible d'énergie provenant de la biomasse; l'évaluation des impacts pouvant provenir de cette utilisation de la biomasse pour fin énergétique; l'etablissement de plantations monoculturales.

INTRODUCTION

In general there is no scarcity of mensurational data on Canadian forests. And, since the ENFOR program started, a number of projects have been financed to develop equations to estimate forest tree biomass. However, not much (either quantitative or qualitative) information is available concerning the nutrients removed from the harvested sites. Until recently the possible loss or reduction in forest productivity due to such removal of nutrients from sites was not considered a serious problem. With widespread use of new harvesting machines the total removal of all the forest biomass has become an inevitable reality. This, of course, may appear to be sensible from an economic and machine efficiency point of view; but unfortunately the consequences of increased nutrient removals from the site and the subsequent loss of forest productivity are ignored or considered inconsequential. Hence, there is an urgency to evaluate the significance of removing all the forest biomass from sites and the nutrients associated with them.

This report consists of data generated, through an ENFOR (P337) study, to establish biomass and nutrient inventory characteristics of commercially important forests of New Brunswick. Evaluated here are the possible contributions of two main variables; tree species and productivity classes, on the quantities of excess biomass and nutrient removals resulting from intensive (whole tree) harvesting, and the potential damage sustained by forest land.

MATERIALS AND METHODS

Study Area

A part of the data from the ENFOR study was reported at the previous Bioenergy R and D seminar held at Vancouver (Mahendrappa et al. 1987). Presented here is a complete set of data on the biomass and nutrient inventory characteristics of forest stands, in New Brunswick, that represent most of the commercially important tree species. For the study 25 forest sites located throughout New Brunswick (Fig. 1) were selected. Mensurational and site classification characteristics of each stand studied are described in Table 1. As can be seen in Table 1, the sampling locations represent eight tree species (three hardwoods and five softwoods). Each species was represented in at least three locations. Each of the tree locations was selected to represent either good, medium or poor site class as determined under field conditions. The site class evaluation under field situations is based on the height/free age relationships of representative dominant and codominant trees. This method agreed well with SI_{50} values (Table 1) in almost all cases. It is, however, clear that the site class described in terms of height growth at a fixed

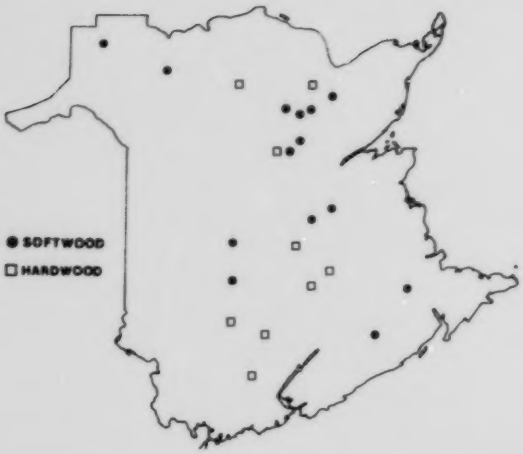

Figure 1. Sampling locations in New Brunswick.

age (50 years for example) and mean annual increments (Table 1) are preferable.

Sample collection and chemical characterization

At each location two plots were established and in each plot five trees were felled for sampling. Bulk samples of foliage were collected from each felled tree and analyzed separately for different elements (MacDonald 1977). Representative samples of small and big branches were similarly gathered and pooled for analysis. Stemwood and stembark samples were collected at three locations from each tree: at stump height, just below the live crown and the midpoint between the live crown and stump height. Using the detailed mensurational data obtained for each plot the biomass at each sampling location was calculated according to the equations developed earlier (Ker 1982). By integrating the biomass data and chemical characteristics of different tree components the total quantities (on a per hectare basis) present in and those removed from each sampling locations through conventional and whole tree (WH) harvesting were calculated. Also the foliar chemical characteristics data were subjected to discriminant canonical analysis and principal component analysis to delineate site classes based on the possible interactive effects of nutrient and non-nutrient elements found in the foliage samples.

RESULTS

Site quality related to foliar chemical characteristics

The information in Figure 2 shows that each tree species has its own niche in terms of its nutrient characteristics and within each species site quality effects are discernible based on

Table 1. Mean annual increment and SI_{50} calculated for stands on the sites sampled for this study

Site No.*	Major Species	Mean Annual Increment Total m^3/ha/yr	Mean Annual Increment Merch. m^3/ha/yr	Site Class SI_{50} (m)	Site Class Field Method*
5	Black spruce	4.3	3.6	18.0	Good
2	Black spruce	4.1	2.5	12.2	Medium
13	Black spruce	0.7	0.3	7.0	Poor
16	White spruce	6.7	5.6	18.5	Good
24	White spruce	4.4	3.0	14.0	Medium
25	White spruce	3.0	2.6	15.2	Poor
4	Balsam fir	5.7	4.8	16.0	Good
15	Balsam fir	5.2	4.5	17.4	Good
12	Balsam fir	3.3	2.4	9.6	Medium
10	Balsam fir	5.5	2.2	15.0	Poor
23	Eastern larch	7.8	7.0	25.8	Good
20	Eastern larch	3.3	2.7	18.0	Medium
22	Eastern larch	0.6	0.5	10.6	Poor
1	Jack pine	5.9	5.0	19.4	Good
11	Jack pine	3.6	3.3	16.9	Medium
14	Jack pine	4.4	4.0	17.8	Poor
6	Aspen	15.6	14.3	17.0	Good
8	Aspen	7.2	6.5	13.0	Medium
17	Aspen	2.4	2.0	13.0	Poor
9	Birch	5.1	3.4	17.0	Good
7	Birch	3.1	3.0	15.6	Medium
19	Birch	2.0	1.9	15.5	Poor
3	Maple	4.4	3.9	16.8	Good
18	Maple	3.1	2.6	12.5	Medium
21	Maple	1.9	1.7	13.0	Poor

*This was based on free-age height relationships of five dominant and co-dominant trees (see text for details)

foliar nutrient levels. It should be pointed out that on the X-axis the major positive contributors to the delineation of species and sites include nitrogen, potassium and zinc while aluminum is the major negative contributor. On the Y-axis, however, the major positive contributor is aluminum while P, K, and Mn are very minor negative contributors. There are two distinct observations to be noted in this diagram. The first is that non-nutrient elements such as aluminum and zinc are important in delineating species and site classes. Secondly, the species effects are distinctly separated from one another. The deciduous species, on the right, are clearly separated from the evergreens, particularly when axis 1 and axis 3 of canonical discriminant analysis are plotted on the X and Y axis of the diagram respectively. The results provide important clues that are helpful for plantation establishment. The need to match each site with a more suited species for maximizing sustained forest productivity is quite evident.

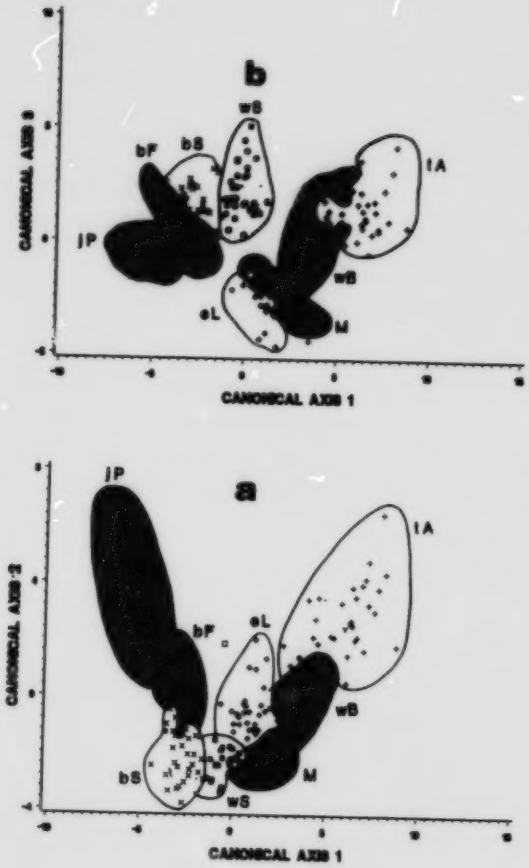

Figure 2. Delineation of species and sites based on canonical analysis of foliar analysis data: in (a) the canonical coefficients of axis 1 and axis 2 and in (b) the canonical coefficients of axis 1 and axis 3 are plotted.

Conversely, it is possible to recognize the potential for site degradation due to a mismatch of species and site. The results also help to understand and provide some explanations for the sequences of successions in different forest regions.

In Figure 3 the observed concentrations of nitrogen in different tree components are presented. It is clear that foliage and branches contain a much higher concentration of nitrogen than stemwood and stembark. This is also true for most other elements. To evaluate the significance of nutrient removal due to whole tree harvesting the total quantities of nitrogen in different components were calculated (Fig. 4). It is evident from Figures 3 and 4 that both the concentrations and quantities of nutrients contained in different components vary among species and sites. Thus, it is easy to visualize that leaving behind nutrient rich components of trees can result in lesser depletion of the nitrogen

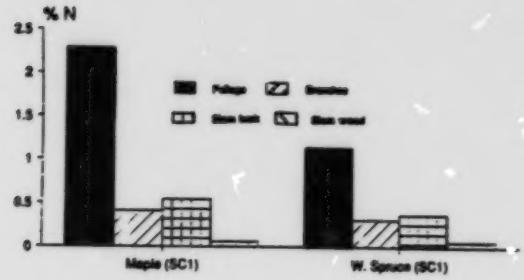

Figure 3. The observed concentrations of nitrogen in different components of white spruce (wS) and maple (M) trees.

capital of soils as compared to the depletion caused by whole tree harvesting operations in which the branches and other nonmerchantable portions of trees are either used for other purposes (for energy, for example) or burned along the roadside.

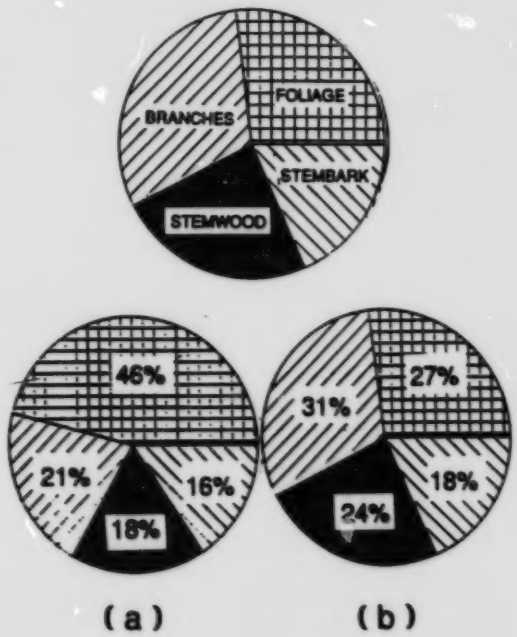

Figure 4. The quantities (kg/ha) of nitrogen in different components of white spruce (wS) and maple (M) trees.

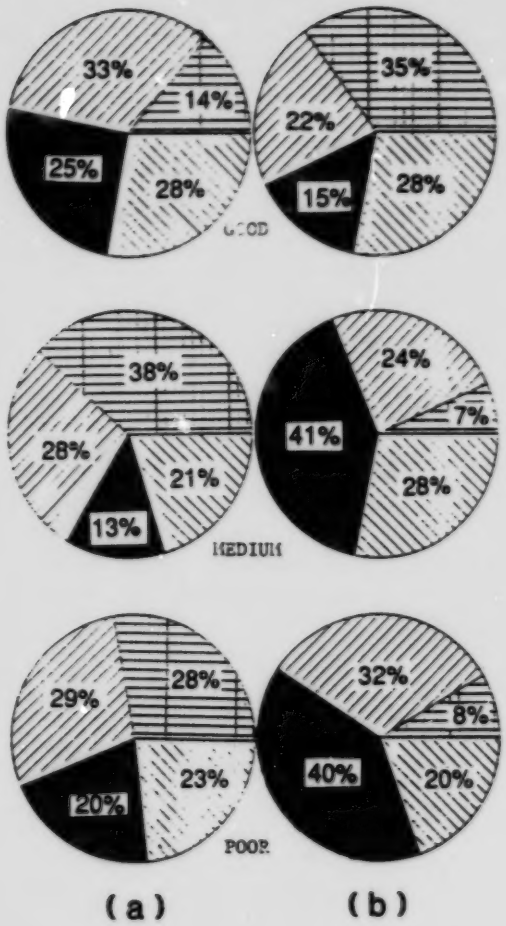

Figure 5. The observed distribution of total cations (Ca + Mg + K + Na) in different components of trees: (a) = white spruce and (b) = maple (see figure 4 for the legends).

Other consequences of intensive harvesting appear to be an excess loss of cations, such as Ca, Mg, Na, and K, and the resultant increased potential for site degradation through soil acidification (Rosen 1988, Mahendrappa 1986, Mahendrappa et al. 1987, Lundkvist 1987). In Figure 5 some quantitative data are presented to substantiate this concept. Presented on the left (a) a set of pie charts are the data for white spruce stands growing on three different site classes. On the right (b) are the corresponding data for maple stands. There are differences between the quantities of cations contained in different components of white spruce and maple stands studied. Also some differences can be found within each species depending on site classes. An overall difference between the quantities of cations in nonmerchantable portions of trees in white spruce and maple stands are presented in Figure 6. The quantities represented by each bar in Figure 6 are indications of percent increase in the loss of cations due to whole tree harvesting as compared to the quantities lost through conventional harvesting methods. Although the concentrations of various cations in the maple stands are higher than in the white spruce stands, the percent increase in the loss of cations due to whole tree harvesting is less in maple than in white spruce. This difference is true for most deciduous and evergreens and is due to the fact that a larger proportion of cations are associated with the nonmerchantable tree components of evergreen than the deciduous trees. Nonetheless, it is unequivocal to state that whole tree harvesting results in an excessive depletion of cations from harvested sites. The degree of depletion also depends on the original productivity of the stands harvested. Thus, both site quality and species should be carefully considered in deciding the method of harvesting. Also, it is imperative to match most suitable species with the site for plantation establishment.

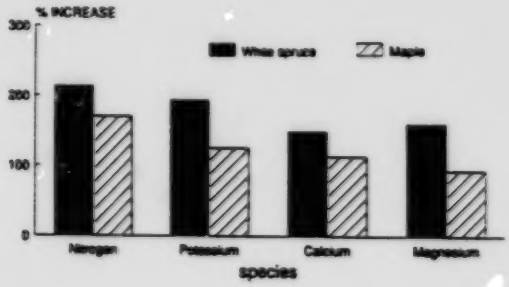

Figure 6. Percent increase in the removal of cations due to whole tree harvesting (as compared to conventional harvesting) of white spruce and maple stands growing on different sites.

CONCLUSIONS

(a) Significant species and site effects on biomass and nutrients in the forests of New Brunswick are recognizable.
(b) Foliar nutrient characteristics of trees are related to site productivity classes.
(c) Intensive harvesting and site degradation are inter-related. The cause and effect relationships between them are dependent on site class and tree species.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the patience and help of Mr. D.G.O. Kingston in preparing the poster.

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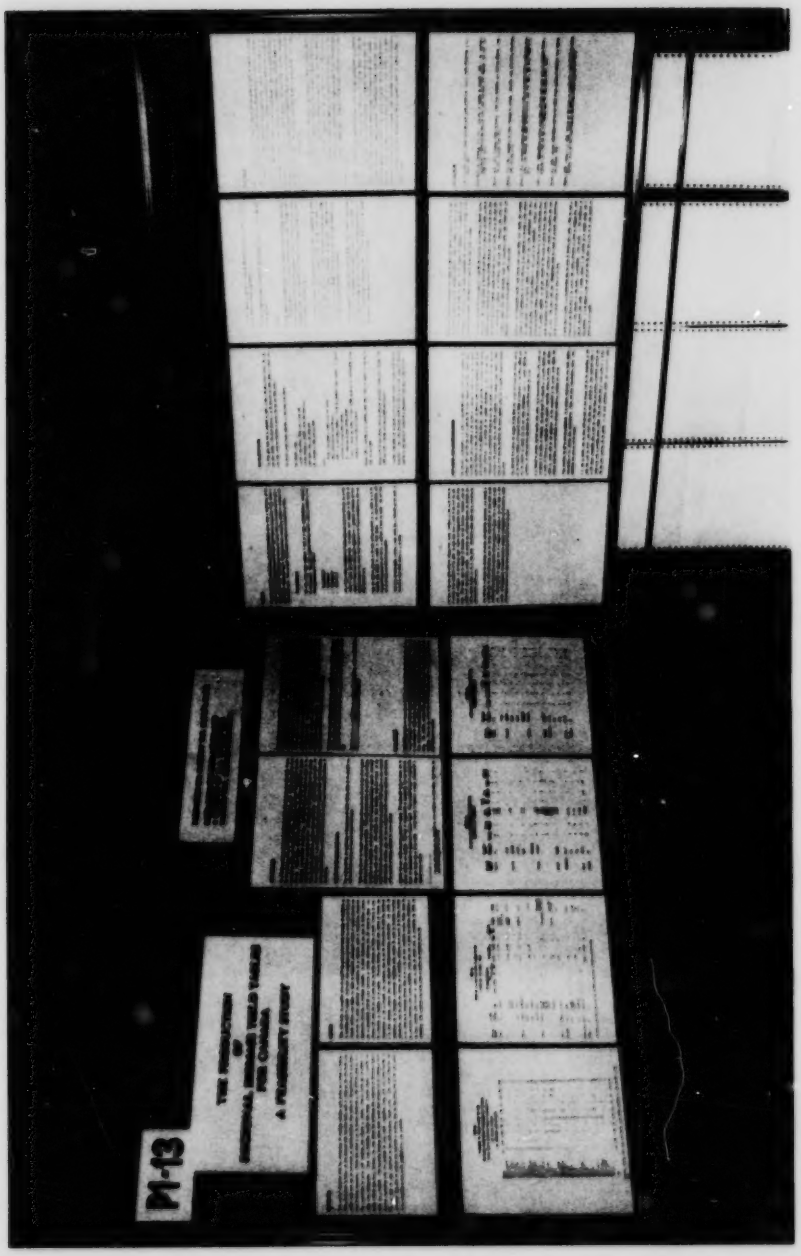
M-13

THE PRODUCTION OF REGIONAL BIOMASS YIELD TABLES - A FEASIBILITY STUDY

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SUMMARY

This study considers that the production of regional biomass yield tables for Canada is feasible. This conclusion is based on the premise that the data bases used to construct the provincial yield tables exist and can be converted to regional biomass yield tables by the application of appropriate tree biomass equations. There also exists a set of factors produced by the ENFOR program from the conversion of gross merchantable tree volume to weight. Factors were also developed for other tree components - bark, top, branches, foliage and stump. Further factors to predict the stand volume and hence biomass, for trees below the minimum size measured in permanent sample plots, are available. The resulting biomass yield tables would then account for all Canadian forest biomass excluding only the biomass of roots, lesser vegetation, litter, duff and other biomass in the soil and on sites classified as non-merchantable forest cover. This study identifies the necessary data and its sources and provides a working plan for the production of the yield tables. It recommends a pilot study, suggests a six year schedule.

RÉSUMÉ

Dans cette étude, on considère qu'il est possible de produire des tables régionales de rendement de la biomasse pour le Canada. Pour tirer cette conclusion, on s'est basé sur le fait que les bases de données utilisées pour établir les tables de rendement provinciales existent et qu'elles peuvent être converties en tables régionales de rendement de la biomasse grâce à l'application d'équations appropriées décrivant la biomasse forestière. Il existe également une série de facteurs produits par le programme ENFOR pour convertir le volume marchand brut des arbres en masse. Des facteurs ont aussi été mis au point pour les autres éléments de l'arbre, à savoir, l'écorce, la cime, les branches, le feuillage et la souche. D'autres factuers existent pour prévoir le volume des peuplements et, par conséquent, leur biomasse, dans le cas des arbres dont la taille est inférieure à la taille minimal mesurée dans les placettes d'échantillonnage permanentes. Les tables de rendement de la biomasse résultantes rendraient alors compte de toute la biomasse forestière canadienne, sauf de celle des racines, de la végétation mineure, de la litière, de la litière feuillue et du reste de la biomasse présent dans le sol et sur les sites considérés comme faisant partie de la couverture forestière non commercialisable. Cette étude fait le point des données nécessaires et de leurs sources; elle fournit en outre un plan de travail pour la production de tables de rendement. Elle comprend une étude pilote et prévoit un calendrier de six ans.

INTRODUCTION

The ENFOR program has produced a national inventory of forest biomass (Bonnor, 1985). It used the same format as "Canada's Forest Inventory 1981" (Bonnor, 1982). Biomass estimates have been produced by species for broad forest types (softwood, mixed wood and hardwood) for each Province. These biomass estimates have been generated by applying individual tree biomass relationships to provincial inventory data. This biomass inventory presents an image of the Canadian forest at one instant in time. Consideration of the dynamic aspect of the Canadian forest, its growth and yield, is a natural sequel to inventory. Regional biomass yield tables* will be a valuable addition to the ENFOR program and will have a number of uses. An understanding of the regional distribution of yield is essential to any consideration of the potential utilization of this resource.

*Growth and yield may be expressed as yield equations or yield tables. Both terms are used interchangeably in this study.

Need for Regional Biomass Yield Tables

The requirement for the prediction of the quantity of forest biomass likely to be available for fuel in the future creates the need for biomass yield tables.

Yield tables become an essential forest management planning tool as the harvesting of the original first growth stands approaches completion. These yield tables predict the quantity and dimension by species of merchantable wood that a forest site is capable of producing. Biomass yield tables predict the total tree weight. This includes stem, bark, branches, twigs and foliage. In this study, roots and other plant material below ground are excluded. Wood assigned to other forms of utilization, such as lumber, pulp, etc. can be deducted from the total yield when the determination of the quantity of biomass available for fuel is required.

Planning fuel and energy supplies is regional in nature. The source and forms of energy and the options available are regional. The cost of transportation of natural gas, coal and electricity limits the distribution of supply to a tributary region. There are also long-term considerations when the energy has a finite supply. Forest biomass is therefore a major consideration in regional energy supplies.

The regional user of this forest biomass requires to know what to expect in order to be able to design equipment to manufacture a salable product, i.e. energy, heat or lumber etc. In the short-term he requires a description of the raw material as to quantity, size, species, quality, availability, location and price. In the long-term, he wants to know about the future supply, how it may change as to size, quality, distance from the mill, availability, likelihood of loss by fire, pests or disease, disaster or regeneration delay and price. The short-term requirement is satisfied by inventory records. The long-term requires a management plan dependent on productivity estimates, site classification, yield estimates, age-class distribution, estimates of likely losses, benefits from silvicultural treatments, protection, etc. Biomass yield tables are one of the elements a planner needs to assist the user in his decision making.

The publication of regional biomass yield tables should satisfy the demand and requirements of planners, policy makers, developers and entrepreneurs who are concerned with a continuing supply of biomass fuel for conversion to energy from a renewable resource on a regional or national basis.

The forest resource is renewable forever given the right management: it can supply Canadians with energy when other sources are exhausted or fully utilized.

DATA SOURCES

The following 4 tables list the number of trees that were cut and measured in the forest and from which measurements the biomass equations were derived by species for each region. The species in each region for which regular yield tables are available are also indicated by an underline. These yield tables are also described including type, management regime, data source, format and author. The variables involved, both independent and dependent are indicated in the final tabulation. These are the sources from which the basic data required to produce regional biomass yield tables can be obtained.

RESULTS

The result of studying the available data and methodologies was to select a modification of the method of analyzing Permanent Sample Plot (P.S.P.) and Temporary Sample Plot (T.S.P.) records to produce yield tables as recommended by Reimer and Lussier (1984) as the logical and best way to build Canadian biomass yield tables. The relevant data are provided in Appendix I of Reimer and Lussier's publication. Some especially relevant parts are abstracted and modified as follows:

Basic Model Format

The basic model format suggested is that of a static multiple-equation, component forecasting system. The system suggested includes separate estimating equations for the following components of stand yield:

1. Stand top height
2. Stand density
3. Stand diameter
4. Stand volume

Such a format enables development of models with good predictive behaviour for a wide variety of species and available data. In practice, each equation in the linked set attempts to describe the mensurational relationship of a parameter of interest; the more complex parameters e.g. volume, being functions of the simpler parameters (e.g. stand top height and basal area).

Stand top height is proposed as the basic driving parameter of the system as it is the parameter least affected by changes in stand density. All stand descriptions and parameter relationships are tied directly or indirectly to stand top height. Age and basal area are the other two independent parameters.

Yield tables, as noted earlier, represent a static rather than a "dynamic" growth model in the sense of Alder (1980), Section 5.2, p. 63 et.seq.

Specific Model Format

The basic data bank will be required to supply volume identified as to species, site, age and stand density. The stand structure is to be described by DBH, stems per hectare and basal area, which are functions of species, site, age and stand density.

The specific model format suggested for this study is as follows:

Site: Height = f(age)
Average Stand Density: Basal Area = f(site, age)
Volume: Volume (or weight) = f(site, age, basal area)
DBH: DBH = f(site, age, basal area)
SPA: Defined by basal area and DBH

Where:
- Height = site height in metres (from site curves)
- SPA = stems per unit area (hectares)
- DBH = average stand diameter. Could be quadratic mean diameter, or another expression of average stand diameter.
- BA = basal area in square metres/hectare
- Volume = volume per hectare in cubic metres (gross or net merchantable to any standards for which data are available).

Because DBH is defined as the quadratic mean DBH, stems per hectare are defined by basal area and DBH.

Several levels of stand density should be specified according to experience, perhaps 75%, 100% and 125% of average stocking (average stand density).

Currently, this model can be applied to all provincial inventory systems except for New Brunswick "... but... most provinces would still have to derive the component equations required for each species of commercial or management importance in their land base..."

If a growth model is required, it could be achieved by using a net basal area growth function instead of average stand density.

This basal area growth model would then be: the increment of basal area = f(site, age and starting basal area).

Summary

Multiple-equation component-types of yield forecasting systems have been widely used since the development of computer-based simulation models. Most component-type simulation models have been developed specifically for use in analyses of intensive forest management regimes but the benefits of component-type forecasting systems are equally valid for natural stand forecasting.

The recommended standard yield model to be used as a basis of comparison for other growth and yield models currently in use in Canada and the United States, is a component-type model. The model is a whole stand model, predicting stand average parameters. However, the format of the model lends itself easily to modification for stand-table projection or to managed-stand simulation; the choice being dependent upon available data and associated management requirements.

The model suggested is a height-based forecasting model. Height is used as the driving parameter as it is the parameter least affected by variations in stand density. In addition, the use of height can simplify model construction and field application if only a single set of mensurational relationships need be derived which are to be equally applicable to all heights and site indices for a particular species.

DISCUSSION

There is undoubtedly a wealth of data in Canada that has been or could be utilized to develop yield tables. Bickerstaff and Hostikka (1977) have documented much of this and there is probably more, especially work done by individual forest companies that could be utilized. Most of this work is local in scope and the study designs, fieldwork, compilation or analysis may be deficient or incomplete. Theoretically it would be possible to complete and utilize this work but it could be a considerable undertaking. A more efficient way to stimulate their utilization might be an "extension service" type approach. Sample designs, field instructions, analytical packages (including mathematical procedures and computer programs) could be made available and promoted for local use across Canada. This would encourage and upgrade the quality of the use of yield tables in Canadian forest management.

At the provincial management levels, yield tables are appreciated and used to varying degrees. There are some notable gaps, for example in Manitoba. There are some instances where the type of yield table information in use is not fully satisfactory to the users who would like to upgrade it, e.g. Newfoundland and New Brunswick. There are cases where the yield tables in use are sophisticated and advanced, but still do not represent the forest in the best possible way, e.g. Ontario using normal tables with their inherent problems in application and British Columbia using tables based on temporary sample plots. Permanent sample plots would give more truly characteristic results.

The tables would represent the dependent variables, volume (total and merchantable by utilization standard(s)), basal area, mean diameter, top height and number of trees per hectare for each age class by top height class. Tables would be produced on a regional basis for all major species present. Mixed species stands would be treated as single species stands of the leading species or as single species stands of a species association. Corresponding biomass yield tables would be produced presenting tree components by mass, oven-dry and green. The tree components would be bole, bark, branches and foliage. Branches may or may not be broken down in size classes depending on the size of the trees in the region. These yield tables would be a joint production of the provincial and territorial inventory services in cooperation with the regional offices of Forestry Canada.

The basis of the yield tables would be existing P.S.P. records. Validation of site curves would be a first step in the preparation of the tables. In some cases, some or much of the work has been done and is available. In the Prairies region, Alberta and Saskatchewan have good yield table bases. These tables might be validated for Manitoba and the Northwest Territories using the limited P.S.P. data presently available. The biomass tree component equations are available and can be applied to these two sets of yield tables. The Prairies region might well be considered as appropriate for a pilot project.

The exercise in considering the feasibility of biomass yield tables has limitations. It is possible in a general sense to collect information upon the current scene and status of yield tables across Canada but it is not possible to assemble detailed accounts of exactly what is available in each case. This should not be necessary prior to a decision to proceed to the next stage of this project. If the principles and general practices proposed are reasonable and the expected results and outcome seem to be of value, then finer details can be left to the next phase.

CONCLUSION AND RECOMMENDATIONS

The approach recommended is to obtain a representative subset of the basic permanent and temporary plot data that was used to generate the various regional yield tables outlined earlier. This basic data will be obtained in the format of a tree list for each plot giving the species, height and diameter of each tree on each plot. In addition, other relevant parameters such as site index and location will be added to each plot. This tree list will then be converted to the various biomass components. An estimate of the biomass represented by small trees less than 7 centimetres and non-commercial tree species will also be added to each plot; this may be done according to the procedure used in the ENFOR Canadian forest biomass project (Bonnor, 1985). Once the basic data are assembled, the model suggested earlier will be applied to generate biomass yield tables.

This approach will require the pooling of plot data from various provincial and federal sources. As the proposed biomass yield model is driven by height as expressed by site index, special care will be required to ensure that the site index relationships used by various agencies are consistent. In some cases, this may require the use of standardized height age curves.

It is feasible to produce regional biomass yield tables. It is recommended that a pilot study for one species in one region be developed. The pilot should be completed in 12 months elapsed time. It would be followed by completion of that region's remaining commercial species, and thence region by region until all are completed. At the conclusion of the project, both regular and biomass yield tables would be available for all major commercial Canadian tree species.

These estimates are global and not guaranteed. It is common experience that data bases, whether computerized or not, contain some inconsistencies. These can cause unpredictable delays. Skill, dedication and patience will be needed.

It is easy to predict that the most difficult part of this project will be the assembling of the yield data from the P.S.P.'s and T.S.P.'s that was used to generate the yield equations (Table 1). It will require remarkable skill to take the yield data tables and produce compatible equations and tables from what is available across Canada. This will require skill to create equations to which the tree mass equations can be applied. It will need intelligent transfer and substitution, using the best and closest approximations from region to region and species to species to fill the gaps such as exist in Manitoba and the Northwest Territories. What is available will need to be used to fill the holes and bridge the gaps. It will require an imaginative yet sensitive forest mensurationist who is aware of the pitfalls, understands the subject and has the courage to put the whole thing together. The result will be open to review and further critiques.

The primary objective for this project is to consider the feasibility of developing regional biomass yield tables. The proposed method of developing such tables is to apply the nationally produced ENFOR program's individual tree component biomass equations to selected provincial yield data. This method should give regional biomass tables that would cover Canada, and at the same time reveal opportunities to upgrade the provincial yield table base. Biomass yield tables will complement regular yield tables expressing weight by components rather than volume and tree dimensions. They will not be an alternative to regular yield tables.

There is a very considerable benefit from having valid yield tables, both regular and biomass, available for forest management. It is very difficult, if not impossible, to manage a forest without valid yield tables. The cut control, which is the crux of any forest management, must have accurate prediction of the future production of the forest to be meaningful. Accurate future production estimates demand a precise knowledge of the productivity of the forest land area which is at the manager's disposal. In the past, because of the extent of natural forest and the forest capital accumulated in old growth mature and overmature timber stands, this question has been slow to arise. That time is now past. Management plans not based on accurate yield prediction will be in error by either cutting too much or too little.

In more specific terms, it is recommended that the work of Reimer and Lussier (1984) be used as a basis and that those parts of the country that require assistance be aided in bringing their yield tables to a basic standard by the method recommended. This project, i.e. the production of regional biomass yield tables for Canada, appears to be feasible given skilled people and is recommended. It will require a one year period for the pilot and a five to six year period for tables for all of Canada.

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TABLE 1

NUMBER OF TREES SAMPLED FOR BIOMASS FROM WHICH BIOMASS EQUATIONS HAVE BEEN DERIVED AND AVAILABILITY OF YIELD TABLES BY SPECIES AND REGION

Species	B.C.	Yukon	Prairies	NWT	Ont.	Que.	N.B.	N.S.	NFLD	Total
Coastal Douglas-fir	49	-	-	-	-	-	-	-	-	49
Sitka spruce	40	-	-	-	-	-	-	-	-	40
Western red cedar	70	-	-	-	-	-	-	-	-	70
Interior Douglas-fir	41	-	-	-	-	-	-	-	-	41
Ponderosa pine	42	-	-	-	-	-	-	-	-	42
Western hemlock	70	-	-	-	-	-	-	-	-	70
White spruce	105	368	60	61	75	79	-	44	169	961
Englemann spruce	43	-	-	-	-	-	-	-	-	43
Pacific silver fir	45	-	-	-	-	-	-	-	-	45
Grand fir	40	-	-	-	-	-	-	-	-	40
Western larch	41	-	-	-	-	-	-	-	-	41
Western white pine	40	-	-	-	-	-	-	-	-	40
Lodgepole pine	98	149	60	-	-	-	-	-	-	307
Mountain hemlock	39	-	-	-	-	-	-	-	-	39
Black spruce	60	302	60	51	115	734	-	49	318	1,689
Subalpine fir	89	-	60	-	-	-	-	-	-	149
Yellow cedar	41	-	-	-	-	-	-	-	-	41
Black cottonwood	40	-	-	-	-	-	-	-	-	40
Red alder	41	-	-	-	-	-	-	-	-	41
Trembling aspen	40	201	60	56	224	133	-	46	70	830
White birch	40	-	60	-	135	101	-	45	275	656
Shore pine	40	-	-	-	-	-	-	-	-	40
Jack pine	-	-	60	56	139	136	-	42	-	433
Balsam fir	-	-	60	-	74	177	-	50	296	657
Larch-Tamarack	-	-	60	56	79	97	-	47	243	382
Balsam poplar	-	-	60	56	90	-	-	-	-	206
Largetooth aspen	-	-	-	-	96	-	-	-	-	96
Yellow birch	-	-	-	-	95	130	50	-	53	328
Sugar maple	-	-	-	-	112	62	45	-	-	219
Red maple	-	-	-	-	63	61	-	49	-	173
Silver maple	-	-	-	-	37	-	-	-	-	37
White ash	-	-	-	-	74	-	47	-	-	121
Black ash	-	-	-	-	26	-	-	-	-	26
Red ash	-	-	-	-	28	-	-	-	-	28
Basswood	-	-	-	-	76	-	-	-	-	76
American beech	-	-	-	-	76	-	-	-	-	76
Black cherry	-	-	-	-	72	-	-	-	-	72
White elm	-	-	-	-	77	-	-	-	-	77
Hickory	-	-	-	-	73	-	-	-	-	73
Ironwood	-	-	-	-	14	-	-	-	-	14
White oak	-	-	-	-	61	-	-	-	-	61
Red oak	-	-	-	-	114	-	-	-	-	114
Eastern white pine	-	-	-	-	77	56	47	-	-	180
Red pine	-	-	-	-	66	53	-	47	-	166
Eastern white cedar	-	-	-	-	84	-	47	-	-	131
Eastern red cedar	-	-	-	-	26	-	-	-	-	26
Eastern hemlock	-	-	-	-	140	-	49	-	-	189
Red spruce	-	-	-	-	-	55	-	-	-	55
Beech	-	-	-	-	-	-	47	-	-	47
Grey birch	-	-	-	-	-	-	-	44	-	44
Total	1,154	1,020	600	334	2,418	1,874	332	463	1,424	9,621

underline indicates that there are regular yield tables available for this species in this region.

TABLE 2.1

GROWTH AND YIELD DATA BASE STATUS BY BIOMASS REGIONS

DESCRIPTION - DATA SOURCE - FORMAT

Biomass Region	Province or Territory	Type	Management Regime: Age: Even	Uneven	Natural	Plantation	Data Source: P.S.P.'s	T.S.P.'s	Format: Table	Equation	Analysis	Author
Pacific	B.C.	Empirical	x	-	x	-	4,739	50,000*	x	x	Chapman-Richards Ek-Payandeh	B.C.F.S.
		Variable Density	x	-	x	-	4,739	50,000+	x	x	Chapman-Richards	B.C.F.S.
	Yukon	None					16					
Prairies	Alberta	Empirical	x	-	x	-	3,155	119	x	x	Monserud	A.F.S.
	N.W.T.	None										
	Sask.	Empirical	x	-	x	-	1,500	21,000	x	-	-	D.P.R.R.
	Manitoba	None	-	-	-	-	93					
Ontario	Ontario	Normal	x	-	x	-	-	-	x	-	-	Plonski(1981)
		Normal	-	-	x	-	-	-	x	-	-	Plonski(1981)
		Variable Density	x	-	-	x	59	-	x	x	Least squares	Evert (1976)
		Empirical	x	-	x	-	347	-	x	-	-	Evert (1975)
							347	-	x	x	Richards	Payandeh
Quebec	Quebec	Empirical	x	x	x	-	7,155	-	x	-	-	S.I.F.
Maritimes	P.E.I.	None										
	N.S.	Variable Density	x	-	x	-	1,765	-	x	x	-	D.L.F.
	N.B.	Empirical	-	x	x	-	1,255	x	-	x	-	D.N.R.
Newfoundland	NFLD	Empirical	x	-	x	64 -	-	1,8	x	-	-	C.F.S.
Totals - 6	12	3					18,813	72,983	12	7	-	10

*The detail in this table is not guaranteed. It reflects information available and interpretation.

TABLE 2.2

GROWTH AND YIELD BY BIOMASS REGIONS

INDEPENDENT VARIABLES

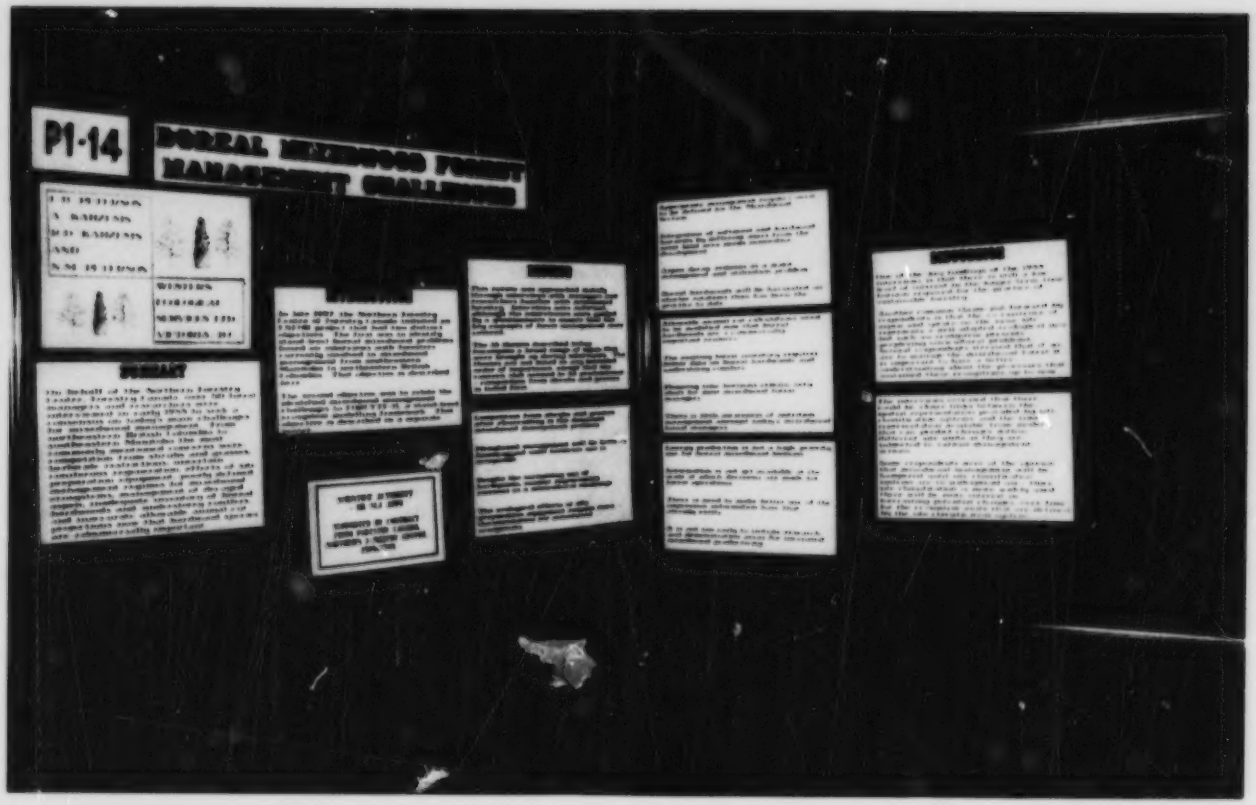
Biomass Region	Province or Territory	Species	Species Groups	Age Ranges	Trees Per ha	Site Classes	Zones	Density Levels
Pacific	B.C.	13	17	0-250	-	4	12	-
		15	6	0-140	-	7	12	3
				0-250		4		
	Yukon	-	-	-	-	-	-	-
Prairies	Alberta	3	3	0-180	-	3	1	-
	N.W.T.	-	-	-	-	-	-	-
	Sask.	7	3	0-70	-	-	8	-
				0-95				
	Manitoba	-	-	-	-	-	-	-
Ontario	Ontario	6	8	0-90	-	3	1	-
				0-190				
		1	-	0-65	-	1	1	-
		1	1	30-90	5	3	1	5
		2	3	30-120	-	-	1	-
				30-140				
		-	1	20-150	-	6	1	-
Quebec	Quebec	7	-	0-50	-	-	27	-
				0-150				
Maritimes	P.E.I.	-	-	-	-	-	-	-
	N.S.	6	3	0-100+	-	6	1	5
	N.B.	2	30	0-100+	-	-	1	-
NFLD	NFLD	6	6	0-100+	-	-	1	-
Total 6	**12**	**27**	**-**	**0-250**	**1**	**1-7**	**53**	**3**

TABLE 23

GROWTH AND YIELD BY BIOMASS REGIONS

DEPENDENT VARIABLES

Biomass Region	Province or Territory	Height	Diameter	Trees Per Hectare	Basal Area	Crown Class	Volume Gross	Volume Merch.
Pacific	B.C.	-	x	-	-	-	1	4
		-	x	x	x	x	1	4
	Yukon	-	-	-	-	-	-	-
Prairies	Alberta	x	x	x	x	-	1	4
	N.W.T.	-	-	-	-	-	-	-
	Sask.	x	x	-	x	-	1	1
	Manitoba	-	-	-	-	-	-	-
Ontario	Ontario	x	x	-	x	-	1	2
		x	-	-	x	-	1	1
		x	x	-	x	-	1	1
		-	x	x	x	-	-	1
		x	x	x	x	-	1	1
Quebec	Quebec	x	x	x	x	-	1	1
Maritimes	P.E.I.	-	-	-	-	-	-	-
	N.S.	x	x	-	x	-	1	1
	N.B.	x	x	-	-	-	1	1
NFLD	NFLD	x	x	x	x	-	1	1
Totals 6	12	10	12	6	11	1	12	13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BOREAL MIXEDWOOD FOREST MANAGEMENT CHALLENGES

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On behalf of the Northern Forestry Centre, over 50 forest managers and researchers were interviewed in early 1988 to seek a consensus on today's main challenges for mixedwood management. From northeastern British Columbia to southeastern Manitoba the most commonly mentioned concerns were: competition from shrubs and grasses after clearcutting; restrictions to the silvicultural use of herbicides; difficulties to achieve white spruce regeneration; uncertainties about the ecological effects of site preparation equipment; ill-defined management regimes for mixedwood ecosystems; difficulties in managing and using decayed aspen; inadequate inventory data on boreal hardwoods and understorey conifers; and inaccurate allowable annual cut projections now that hardwood species are commercially important. Planning time horizons remain very short for most mixedwood forest managers but the increasing use of hardwoods is expected to encourage a shortening of rotations. Today's mixedwood forest managers do not place a high priority on nutrition management nor on the use of boreal biomass for energy production. Several respondents stressed that there are opportunities to make better use of the impressive information base that already exists.

Pour le compte du Centre forestier du Nord, plus de 50 gestionnaires et chercheurs en foresterie ont ete interroges au debut de 1988 au sujet des principaux problemes qui touchent actuellement l'amenagement des peuplements melanges. Du nord-est de la Colombie-Britannique au sud-est du Manitoba, les problemes mentionnes le plus souvent etaient les suivants: competition des arbrisseaux et des graminees apres des coupes rases; restrictions imposees a l'utilisation des herbicides en sylviculture; difficultes a regenerer l'epinette blanche; incertitudes quant aux effets ecologiques de l'equipement de preparation des sites; mauvaise definition des regimes d'amenagement destines aux ecosystemes melanges; difficultes relatives a la gestion et a l'utilisation du tremble pourri; lacunes dans les donnees d'inventaire relatives aux feuillus boreaux et aux coniferes de sous-etage; et inexactitude des previsions des coupes annuelles permissibles, maintenant que les feuillus sont commercialement importants. Les horizons de planification restent tres courts pour la plupart des gestionnaires des forets melangees, mais on prevoit que l'utilisation croissante des feuillus favorisera un raccourcissement des rotations. Les gestionnaires des forets melangees d'aujourd'hui ne donnent pas un haut degre de priorite a la gestion nutritionnelle ni a l'utilisation de la biomasse boreale pour la production d'energie. Plusieurs des personnes interrogees ont insiste sur le fait qu'il serait possible de mieux utiliser l'impressionante base d'information qui existe deja.

INTRODUCTION

In late 1987, the Northern Forestry Centre of Forestry Canada initiated an ENFOR project that had two distinct objectives. The first was to identify stand-level boreal mixedwood problems based on interviews with foresters currently involved in mixedwood management from southeastern Manitoba to northeastern British Columbia. That objective is described here.

The second objective was to relate the identified mixedwood management challenges to FORCYTE-11 (FORest Nutrient Cycling and Yield Trend Evaluator), a stand-level ecosystem modelling framework developed under ENFOR contracts by Prof. J.P. Kimmins and co-workers at the University of British Columbia. That objective is described in a separate report in these seminar proceedings (Peterson and Apps 1989).

DEFINITION OF FOREST MANAGEMENT FOR THE PURPOSE OF THIS REVIEW

From the various definitions of forest management, the one put forward by Baskerville (1983) was selected as the context in which to conduct this review. By Baskerville's definition, "Management consists of controlling biological dynamics over a forest area in such a manner that it is possible to take a continuous flow of various materials or uses from the area without endangering the rate of production of these materials and uses by the resource."

Management is undertaken to ensure future continuity of the forest uses, and to improve the future situation. That is why there is emphasis on the role of forecasting in today's forest management decision-making. In practice, one constraint on management is the difficulty of forecasting development of many different types of stands, on different sites and in response to different kinds of interventions. The emphasis on forecasting establishes a link with simulation models like FORCYTE which include a Management Forecast Activity.

The other important feature of forest management, as defined by Baskerville (1983), is that it requires the integration of four basic kinds of action that regulate forest dynamics: scheduling the harvest; distributing the harvest; renewing the resource; and protection of the resource. No one of these tools constitutes management in itself. Management is achieved by the integration of all four kinds of action over the entire management area and over a time horizon of at least 40 years. This view of forest management, and particularly the 40-year time horizon, is the context in which the evaluation of FORCYTE was conducted.

METHODS

This review was approached mainly through interviews with managers and researchers familiar with mixedwood forestry. Interviews were informal, although the interviewers were guided by a questionnaire to ensure that the key concepts of forest management were covered. Interviewers set out to record the concerns that respondents perceived to be most important, instead of rigidly following the questionnaire.

CHALLENGES AND OPPORTUNITIES FOR BOREAL MIXEDWOOD MANAGEMENT IDENTIFIED DURING 1988 INTERVIEWS

The 16 themes described below encompass a broad range of ideas that were brought up during interviews. The themes are not listed in any intended order of importance, except that the concern that seemed to be predominant - competition from shrubs and grasses - is listed first. The only other stratification of the 16 themes is that the first ten might be viewed as present or immediate concerns; the last six, while reflecting current attitudes or circumstances, deal with possible future trends.

Competition from shrubs and grasses after clearcutting is the dominant mixedwood management problem

There were indications during interviews that the shrub-grass competition problem, while common across the entire Mixedwood Section, may be most intense on moist sites in west-central Alberta in a band from Edson through Whitecourt towards Lesser Slave Lake. In that part of Alberta, the most difficult silvicultural challenge is how to meet the minimum standard specified for conifer regeneration in stands made up of mixtures of lodgepole pine, white spruce and aspen. On some sites, dense aspen suckers are the main deterrent to re-establishment of conifers; on other sites grasses are the main problem.

A key point is that vegetation management is exceedingly important in boreal and mixedwood forestry. Progress is hampered by lack of information on specific reasons for mortality in those species that lose out during episodes of interspecific competition.

Mixedwood management will be severely handicapped until herbicide use is acceptable

Herbicides continue to be one of the key forest management issues, not necessarily for biological or technical reasons but for political and public perception reasons. Manitoba has had more opportunity than Saskatchewan and Alberta to operationally use herbicides as a silvicultural tool. The herbicide dilemma is particularly focussed in the Mixedwood Section because on the best

sites, with finer-textured soils, aspen is normally present whether the forest manager wants this species or not. In Manitoba, where aspen utilization is not yet as widespread as it is in the other three western provinces, the manager faces two choices: i) accept the resulting mixedwood stand and find ways to manage and use both the softwood and hardwood components; or ii) use herbicides to control the currently unused hardwoods. The latter approach is less and less acceptable to the public because it is viewed as 'hardwood elimination' or 'stand conversion' rather than 'mixedwood management'.

Despite the increasing use of hardwoods, conifer regeneration remains as a silvicultural challenge

The interviews revealed a continuing strong interest in coniferous regeneration as the central challenge of mixedwood forestry, particularly where aspen utilization is not well advanced. Some respondents did suggest that the 'how to regenerate conifers' era is coming to an end and that the focus must shift to advance identification of sites that will grow conifers most easily and those best suited for regeneration of hardwoods.

Some respondents were encouraged that forest renewal is being increasingly designed to meet certain target yields instead of simply stocking standards. This is achieved, in part, by adding performance guarantees to stocking.

The ecological effects of site preparation equipment require more documentation for mixedwood ecosystems

The use of Scandinavian spot scarifiers and disc trenchers in Canadian boreal and mixedwood forests is now common. As operational experience with this equipment increases, suitable sites and limitations are being identified and prescriptions for site preparation are becoming more specific. However, it is the great diversity of site preparation equipment that contributes to lingering uncertainties about the ecological effects of site preparation operations.

Slash management can be viewed as a sub-set of the overall question of ecological effects of site preparation equipment. Slash was identified by some as the single most important silvicultural problem, mainly because of its hindrance to operation of silvicultural equipment.

Soil temperature is considered to be an important factor when deciding how to regenerate mixedwood sites; the most successful site preparation methods for spruce are generally those that warm up the soils. Some respondents were of the opinion that soil moisture is not a limiting factor in Alberta boreal mixedwood forests except in May of some years.

Appropriate management regimes need to be defined for the Mixedwood Section

During the 1988 interviews, respondents talked about management regimes for mixedwood forest species more than any other topic. The diverse ideas offered by respondents can be grouped under three general categories: management regimes with a coniferous focus; those with a hardwood focus; and those with a mixedwood focus. However, it is evident that despite efforts to manage for a given species, whether it is white spruce or aspen, the end result is nearly always going to be a mixedwood stand because of natural addition of the other species. There is growing uncertainty whether it is good policy to automatically manage for the species that existed on a site before harvesting; on some sites the pre-harvest forest may not have contained the species best suited to the site.

There are still expressions of uncertainty about acceptance of hardwood regeneration on areas where conifers have been harvested, but if aspen is well suited to the site this uncertainty should be diminished as hardwood utilization increases. Up to now there has been widespread acceptance that in mixedwood stands 'what you have is what you're going to get' when it comes to regeneration after a disturbance. Some respondents did question this acceptance because it is becoming less and less defensible as a management goal.

Many respondents suggested that management for conifers in the Mixedwood Section centres around two key questions: i) how should we manage overmature mixedwood stands where there are strong incentives to selectively remove the large softwoods but little incentive to handle overmature hardwoods that have exceptionally high percentages of cull; and ii) how should we manage and harvest mixedwood stands to give maximum protection to advance softwood regeneration?

Most respondents stressed that mixedwood management problems are substantially more diverse than the usual spruce-aspen focus. There is an important economic aspect to the question of how to manage and utilize stands that have a prime overstorey of aspen with an

established spruce understorey. One respondent stressed the need for criteria by which to project the value of understorey spruce to compare with the value of overstorey aspen of different ages and heights. Such economic analyses are difficult to conduct now because there are no well established values to place on the hardwood resource.

Integration of softwood and hardwood harvests by different users from the same land area needs innovative development

Methods to encourage integration of softwood use and hardwood use requires innovation. There is a need to simplify the removal of hardwoods from lands allocated to softwood licensees and vice-versa. When the hardwood and softwood harvesting rights are held by two different parties there are a number of operational challenges, mainly because delivery schedules, logging methods and costs differ between hardwoods and softwoods.

Aspen decay remains as a major management and utilization problem

Despite a long history of pathological studies of the aspen resource, cull and defects remain as major unresolved problems now that aspen utilization is increasing rapidly. During interviews there were several indications that decay and stain influences on aspen utilization continue to create uncertainty amongst those who produce, manage and use this resource. There is a need for methods to correlate the amount of stem decay with outside symptoms of the tree, long before external conks are evident.

Boreal hardwoods will be harvested on shorter rotations than has been the practice to date

Understandably, aspen utilization will be concentrating first on the existing relatively old stands before they become unusable as a result of decay. However, there are indications of a trend towards shorter rotations for aspen than has been the case for boreal conifers.

Allowable annual cut calculations need to be modified now that boreal hardwoods are a commercially important resource

Many of the foresters interviewed commented on present difficulties with allowable annual cut calculations. There are several unresolved questions: what are appropriate criteria for including softwoods and hardwoods in the calculations? Should only large aspen be included? Should only understorey spruce be included? Future allowable annual cuts are expected to be influenced by another variable that was not discussed during the 1988 interviews, the subject of climatic change.

The existing forest inventory requires better data on boreal hardwoods and understorey conifers

Aside from inadequate information on hardwood age-class distribution and hardwood species differentiation, there is a perceived need for greater inventory emphasis on potential productivity in place of the present focus on existing forest cover. Clearly, many areas mapped as non-commercial brush are no longer in that category because they support aspen that has substantial commercial value.

Planning time horizons remain very short for most mixedwood forest managers

Although 80 to 100 year rotations are still common for boreal mixedwood harvests, planning horizons are, in practice, much shorter. One of the key reasons for a short time horizon is the preoccupation of most managers with problems of how to best use the present forest. Although there may be widespread professional interest in ways to create better and more productive forests in the future, there is presently very little field activity directed to this objective.

There is little awareness of nutrition management amongst today's mixedwood forest managers

There was a strong consensus amongst respondents that nutritional status of sites and long-term nutrition management are not important concerns today in mixedwood stands. There is no conspicuous operational interest in forest fertilization in the Mixedwood Section. Several respondents stressed that growing conditions, especially soil temperatures, at the microsite level are more important variables in mixedwood silviculture than are nutrient competition and light competition.

Energy production is not a high priority use for boreal mixedwood biomass

Biomass residues are used in some processing facilities in the Mixedwood Section, but energy production from forest biomass is not of major importance in the region as a whole, partly because of cost-competitive energy from other sources. For example, some primary forest industries in Alberta use only natural gas as an energy source; other processing plants achieve up to 80% of their heat requirements from biomass by-

products of the operation. It is evident that there is current interest in energy from biomass as a by-product from wood residues, but there is little foreseeable use of mixedwood biomass directly for energy production.

Information is not yet available at the scale at which decisions are made for forest operations

There is a relatively large spread in the geographic scale at which decisions are made because different parts of an operation require different levels of detail. In general, however, many operational decisions are made on relatively small areas in the Mixedwood Section. The average cut-block size is around 30 ha because of the mosaic pattern of the mixedwood forest and also to meet aesthetic or wildlife management concerns.

There is need to make better use of the impressive information base that already exists

The under-utilization of existing information that could assist boreal mixedwood management is not unique to that forest zone. The recent review of available information on release of white spruce from aspen overstoreys (Johnson 1986) is an excellent example of how to make better use of existing information. The key is to focus on information, which means putting data in perspective, rather than on data assembly by itself.

It is not too early to initiate research and demonstration areas for increased mixedwood productivity

The tendency for boreal mixedwood stands to occupy the best sites in any local topographic sequence may be contributing to a complacency to implement intensive silvicultural practices, including use of genetically superior stock. The kinds of ecological information needed to encourage more productive uses of mixedwood ecosystems can be expected to change as utilization changes. It is predicted that ecological research priorities for boreal mixedwood tree species will be increasingly defined by what managers and users are doing with individual species.

CONCLUSIONS

One of the key findings of the 1988 interviews is that there is still a low level of interest in the longer-term time horizon required for the practice of sustainable forestry. The interviews provided very few suggestions on how to create forests for future generations and to ensure a sustainable forest industry and a sustainable environment for people.

Another common theme put forward by respondents is that the co-existence of aspen and spruce on the same site represents a well-adapted ecological mix but such an ecosystem presents perplexing silvicultural problems. Several respondents stressed that if we are to manage the mixedwood forest it is important to have a better understanding about the processes that sustained these ecosystems up to now.

The interviews revealed that there could be closer links between the spatial representation provided by site classification systems and the time representation available from models that can predict changes within different site units as they are subjected to various management actions.

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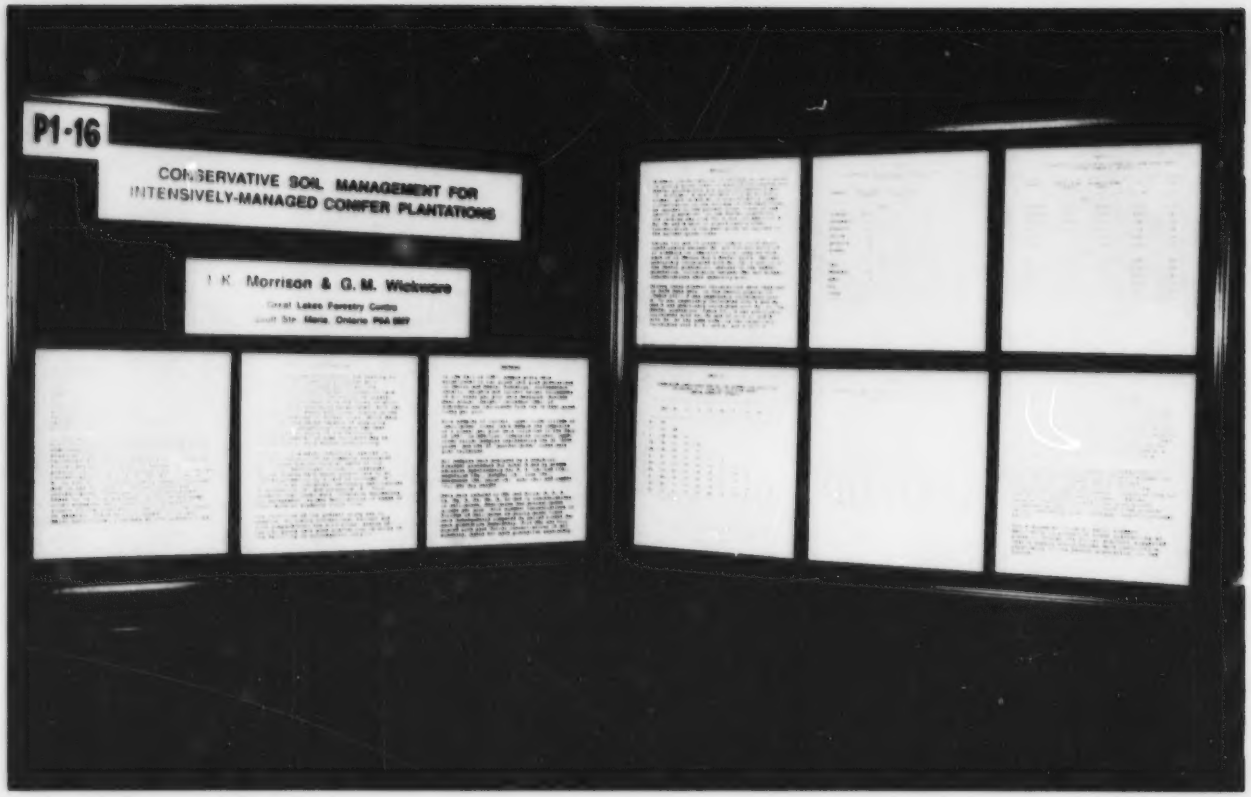
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CONSERVATIVE SOIL MANAGEMENT FOR
INTENSIVELY-MANAGED CONIFER PLANTATIONS
J. K. Morrison & G. M. Wickware

CONSERVATIVE SOIL MANAGEMENT FOR INTENSIVELY MANAGED CONIFER PLANTATIONS

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ABSTRACT In response to increasing demands for wood fiber, Canadian foresters have been actively seeking to increase tree growth rates by developing and implementing more intensive soil management practices. At the same time as there is increased demand for biomass for traditional products, there are prospects that even greater quantities could be removed for the production of energy. This raises questions concerning the drain of nutrients from some sites in harvested products; this drain may be of sufficient magnitude to lead to diminished future site productivity. Jack pine is a principal tree species of northern Ontario and is commonly associated with coarse, glaciofluvial sands of low fertility. Fertilizer trials in unmanaged or extensively managed stands have shown that growth in such situations is commonly limited by a lack of N with, in some instances, secondary deficiencies of P or K, as well. This suggests that, under more intensive harvesting regimes, deficiencies of nutrients could occur in future crops. In our study, we examined the nutrition of young jack pine plantations. In particular, we studied tree foliage for indications of nutrient deficiencies.

RÉSUMÉ Pour répondre aux demandes croissantes de fibres de bois, les forestiers canadiens cherchent activement à accélérer la croissance des arbres en élaborant et en mettant en application des pratiques de gestion du sol plus intensives. En même temps, comme la demande de biomasse destinée a des produits traditionnels s'accroit de plus en plus, on envisage de récolter des quantités plus importantes pour la production d'énergie. Ceci soulève des questions au sujet du drainage des éléments nutritifs dans les produits récoltés sur certains sites, qui pourrait entrainer une diminution de la productivité future du site. Le pin gris est la principale essence du nord de l'Ontario et on le retrouve couramment sur des sables glacio-fluviens grossiers peu fertiles. Des essais portant sur des engrais, réalisés dans des plantations non aménagées ou soumises a un aménagement intensif ont montré que dans de telles circonstances, la croissance est couramment limitée par un manque d'azote accompagné, dans certains cas, de carences en phosphore ou en potassium. Ceci montre que dans des conditions de récolte plus intensives, le récolte suivante pourrait être touchée par des carences en éléments nutritifs. Dans notre étude, nous avons analysé la nutrition des plantations de jeunes pins gris. Nous avons en particulier analysé le feuillage des arbres pour y déceler des carences en éléments nutritifs.

INTRODUCTION

Increased utilization of existing timber stands and increased growth rate of the replacement stands both exert high demands on the mineral nutrient reserves of forest sites. Although many forest soils are considered capable of supplying essential nutrients in perpetuity, some concern has been raised that on soils of inherently low fertility, excessive removals of some nutrients may decrease future productivity (Morrison 1980, Weetman and Algar 1983). As increased biomass utilization and more intensive forest management practices are relatively recent developments, and as tree growth is a relatively long-term proposition, an extensive data base that relates site and treatment to productivity is not yet available.

Jack pine (Pinus banksiana Lamb.) is a major raw material for the northern Ontario forest industry, and has been planted extensively throughout the northern part of the province in recent years (Smith and Brown 1984). The object

of the present study is to examine the nutritional status of typical, young plantations of jack pine in northeastern Ontario after conventional harvest and site preparation.

METHODS

In the fall of 1987, after a preliminary screening of potential sites followed by field inspection, 21 0.04-ha sample plots were established in typical, young jack pine plantations in Denton and Keefer townships in northern Ontario. Both areas had been harvested by conventional cut and skid during the early 1970s. The Denton plantation (12 plots) was planted in the spring of 1977 with 2-0 stock after site preparation by shark-finned barrels and straight-blade windrowing. The Keefer plantation (9 plots) was planted in the spring of 1976 after site preparation with a D-8 crawler tractor equipped with Young's Teeth.

For all trees, total height (m) and current height increment (cm) were determined with height-measuring poles. From these data, mean dominant height (that of the 20 "best-grown" trees per plot) and the current increment of these trees were determined. The mean height and height increment of the 20 "poorest-grown" trees per plot were also determined. For each plot, the following were collected: (1) composite foliage samples of current upper-crown needles of generally well-grown trees (a conventional sampling procedure) prepared from five subsamples, each of which represented four trees; (2) a single composite sample of current upper-crown needles from the 20 "best-grown" (tallest) trees of each plot; and (3) a single composite sample of current upper-crown needles from the 20 "poorest-grown" trees in the same plot. Soil samples were also taken, but results are not included in the present analysis.

In the laboratory, samples were oven dried at 70°C for 48 hours. Each was then ground, weighed and stored in air-tight containers until analysis. Immediately before analysis the samples were re-dried to ensure consistent weight. Samples were analyzed for nitrogen (N) by means of a semimicro-Kjeldahl procedure, and after dry ashing at 500°C and extraction with hydrochloric acid, the following elements were analyzed by means of Plasma Emission Spectrometry : P, K, Ca, Mg, S, Fe, Mn, B, Zn, and Cu.

RESULTS

Mean dominant height in the 12 plots of the Denton plantation (11 years old) was 4.64 m, with a Mean Annual (height) Increment (MAI) of 0.42 m; the current height increment of dominants averaged 0.61 m. For the Keefer stand (12 years old) mean dominant height in 9 plots was 5.81 m, MAI was 0.48 m and current height increment averaged 0.68 m.

Concentrations of the six macroelements and five microelements in current upper foliage of best-grown and poorest-grown trees in the Denton plantation are given in Table 1. Table 2 gives comparable data from the Keefer plantation. In foliage of the best-grown trees in the Denton stand, N, K and Zn were in significantly higher, and Ca and Mn in significantly lower, concentrations than in the poorest-grown trees. In the Keefer plantation, however, the reverse was true for N (i.e., significantly higher concentrations existed in foliage of poorer-grown trees); as well, P, Mg, Mn and B were also in significantly lower concentrations in better-grown trees.

Table 1. Element concentrations (x±SD) in foliage of 11-year-old jack pine trees at 12 plots in Denton Township, Ontario.

Element	Best-grown trees	Poorest-grown trees	Statistics t-value	Statistics P
		mg/g		
N	14.78 ± 1.42	13.83 ± 0.81	2.36	0.04
P	1.34 ± 0.07	1.30 ± 0.11	1.07	0.31
K	4.11 ± 0.87	3.66 ± 0.78	2.03	0.07
Ca	2.35 ± 0.42	2.68 ± 0.28	-3.06	0.01
Mg	0.81 ± 0.08	0.83 ± 0.09	-0.69	0.50
S	0.57 ± 0.11	0.55 ± 0.07	0.70	0.50
		µg/g		
Fe	51 ± 11	48 ± 10	1.06	0.31
Mn	306 ± 59	332 ± 62	-2.13	0.06
B	35 ± 4	36 ± 5	-0.85	0.41
Zn	61 ± 4	55 ± 6	2.37	0.04
Cu	3 ± 1	4 ± 2	-1.52	0.16

Table 2. Element concentrations (x±SD) in foliage of 12-year-old jack pine trees at 9 plots in Keefer Township, Ontario.

Element	Best-grown trees	Poorest-grown trees	Statistics t-value	Statistics P
		mg/g		
N	14.33 ± 1.57	14.87 ± 1.41	-1.91	0.09
P	1.23 ± 0.11	1.34 ± 0.10	-3.27	0.01
K	3.92 ± 0.43	4.27 ± 0.32	-1.81	0.11
Ca	2.85 ± 0.50	2.73 ± 0.29	0.72	0.49
Mg	0.71 ± 0.10	0.93 ± 0.10	-4.97	0.00
S	0.64 ± 0.07	0.70 ± 0.18	-1.18	0.27
		µg/g		
Fe	50 ± 13	41 ± 9	1.64	0.14
Mn	436 ± 152	479 ± 198	-2.19	0.06
B	26 ± 3	34 ± 8	-3.55	0.00
Zn	51 ± 10	57 ± 11	-1.49	0.18
Cu	3 ± 1	3 ± 1	0.00	0.99

Tables 3 and 4 contain simple correlation coefficients (r-values) among MAI and concentrations of the 11 elements in composite foliar samples from the Denton and Keefer plots, respectively. In the Denton plantation, MAI was significantly positively correlated with N, Ca, S and Cu, and negatively correlated with K, whereas correlations between MAI and element concentrations were non-significant in the Keefer plantation.

Strong inter-element correlations were observed in both data sets. In the Denton plantation (Table 3), P was negatively correlated with N, Cu was negatively correlated with K and Mg, and K was positively correlated with Mg. In the Keefer plantation (Table 4) N was positively correlated with Fe; Mn and Zn with S; and B with Zn. At the same time, Ca was negatively correlated with P, K and B, and P with Cu.

DISCUSSION

Although the Keefer plantation was generally better-grown (in terms of MAI and current annual height increment) than the Denton plantation, straightforward comparison is confounded by differences in origin, site preparation, and age, and also because the plots were selected to represent the range of conditions within each plantation.

In general, relationships between measures of growth (principally MAI) and foliar element concentrations were only evident in the Denton plantation. Nitrogen concentrations were higher in the foliage of the best-grown trees than in the poorest-grown trees. Likewise, the regression of foliar nutrient concentration on mean height growth was positive for this element. Calcium and Mn concentrations were lower in the foliage of better-grown trees, which suggests 'growth dilution', in which a fixed amount of element is 'diluted' in a greater biomass. Other elements present interpretation problems, however. In the Denton plantation, for example, K and Zn (in addition to N) were also significantly higher in the foliage of the best-grown trees than in the poorest-grown trees. Although this might be cited as evidence for growth limitation by these elements, covariance with other factors cannot be

Table 3. Correlation coefficients (r) for mean annual height increment and element concentrations in composite foliage samples from 11-year-old jack pine trees at 12 plots in Denton Township, Ontario.

	MAI	N	P	K	Ca	Mg	S	Fe	Mn	B	Zn
N	.562										
P	-.303	-.887									
K	-.679	-.491	.470								
Ca	.575	-.028	.057	-.423							
Mg-	.485	-.555	.541	.909	-.006						
S	.670	.551	-.250	-.323	.133	-.296					
Fe-	.186	.133	-.083	.463	-.387	.333	.289				
Mn	.436	-.071	.013	-.455	.677	-.190	.084	.065			
B	-.475	-.358	.425	.413	.355	.292	-.193	.210	-.606		
Zn	.303	.308	.029	.137	.082	.114	.323	.363	.010	.182	
Cu	.731	.410	-.370	-.909	.476	-.784	.454	.411	.513	.341	.119

Table 4. Correlation coefficients (r) for mean annual height increment and element concentrations in composite foliage samples from 12-year-old jack pine trees at 9 plots in Keefer Township, Ontario.

	MAI	N	P	K	Ca	Mg	S	Fe	Mn	B	Zn
N	-.181										
P	-.233	.523									
K	-.090	.554	.718								
Ca	.405	-.311	-.714	-.608							
Mg	.354	.278	.009	.448	.438						
S	.237	.174	.351	.328	.031	.406					
Fe	.180	.737	.492	.442	-.203	.272	.063				
Mn	.370	.098	.404	.074	.013	-.069	.780	.065			
B	-.225	-.008	.239	.420	-.623	.226	.148	.121	-.152		
Zn	-.155	.446	.240	.562	-.336	.258	.627	.147	.208	.617	
Cu	.179	.136	-.604	-.220	.202	-.021	-.164	.115	.375	.280	.363

ruled out. Further, within the generally better-grown trees (from which the composite foliar samples were taken), both elements were negatively correlated with growth, which suggests a tendency towards 'dilution'. In contrast, in a New Brunswick study of jack pine growth and and nutrition (Hamilton and Krause 1985), growth was highly correlated with higher foliar N,P and K concentrations, as well as with several soil variables.

In the generally better-grown Keefer plantation, fewer relationships with growth were evident in the comparison between best-grown and poorest-grown groups and in the regressions of MAI on element concentrations in the foliar sample. Rather, the several negative correlations between growth and foliar concentrations suggested growth dilutions, with growth being limited by some non-nutritional factor such as moisture availability. Inter-element relationships were common, with the greater number of these probably related to strong linear increases in the concentration of one element with minimal changes in the concentration of the other. In some cases, however, inter-element antagonisms were suggested. In general then, there appeared to be no major limiting nutrient in either of these stands at present.

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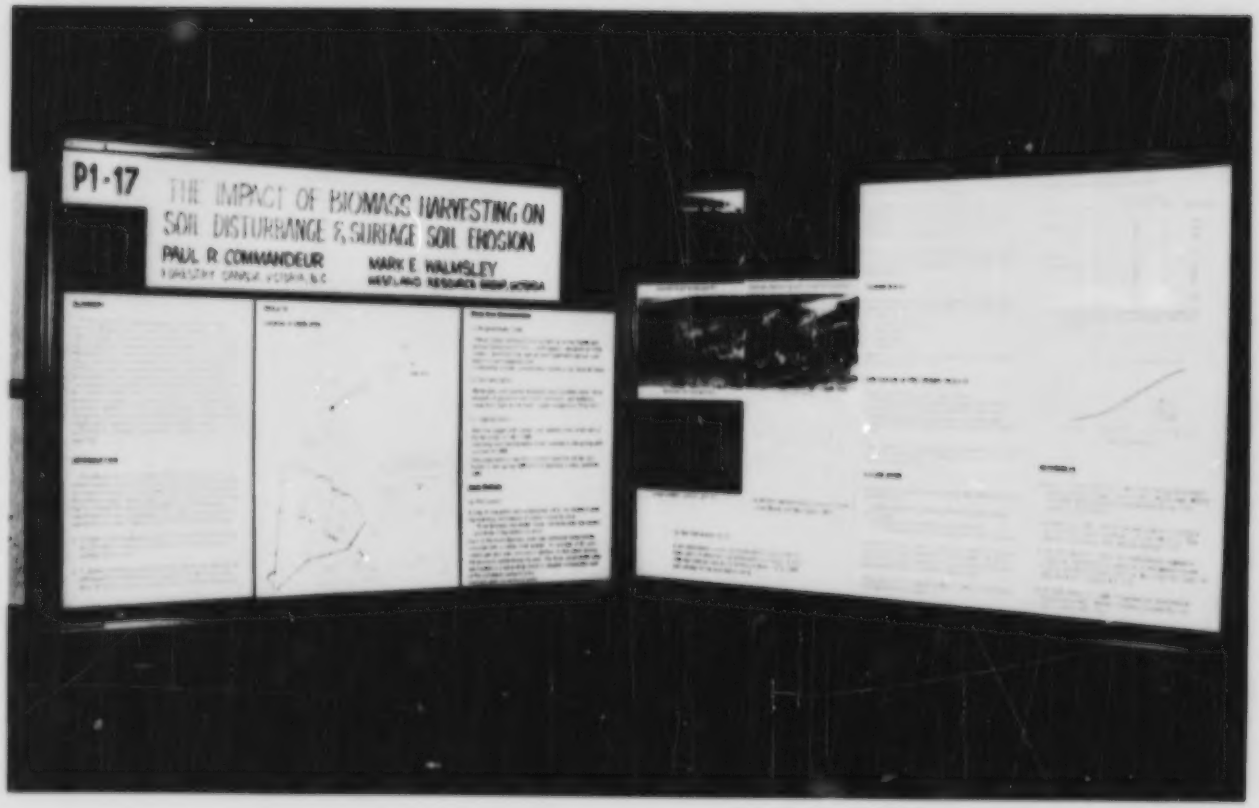
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THE IMPACT OF BIOMASS HARVESTING ON SOIL DISTURBANCE & SURFACE SOIL EROSION
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THE IMPACT OF BIOMASS HARVESTING ON SOIL DISTURBANCE AND SURFACE SOIL EROSION
(Progress Report)

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The objectives of the study are to determine the degree to which biomass harvesting would lead to a reduction in the ability of the soils to resist surface erosion, and the amount of surface soil erosion that can be attributed to such a reduction. The study area, located in the Interior Cedar Hemlock Biogeoclimatic Zone in the Central Interior of British Columbia, was conventionally harvested using rubber tired skidders during the fall/winter of 1987/1988. Three treatments were established and consisted of conventional, biomass and unharvested conditions. Three plots in each treatment were set up as "mini-drainages", the boundaries of which represented, as best as possible, natural topographic breaks. A skidder was used to remove an additional amount of woody material from the three biomass plots.

A postharvest soil disturbance survey revealed that, on average, the biomass harvest plots had 63% total soil disturbance (12% skid roads, 44% skid trails, and 9% other) as compared to 47% for the conventional plots (34% skid trails and 13% other). The biomass plots had 6% more deep (5 to 25 cm) and 10% more very deep (> 25 cm) gouges than the conventional plots. Sediment dams were erected along the contour at the base of each plot. Pins inserted in the ground in a grid pattern in front of the dams will be used to make sediment deposition measurements as a function of time. Three erosion bridges were installed at representative locations in each plot and will provide a measure of net erosion or deposition at these sites.

A climate station was installed at the site and will provide a continuous measure of precipitation, air and soil temperature, relative humidity, wind speed, and solar radiation. To date, a maximum 15-minute rainfall intensity of 5.2 mm (October 1988) was recorded at the site. Site preparation in the form of prescribed fire will be conducted in 1989 prior to planting. The study therefore provides the opportunity to compare pre- and post-fire effects on soil erosion. Using a rainfall simulator, infiltration capacity experiments will be conducted to define which treatment/soil disturbance types are susceptible to the eroding force of water. Upon completion of the study, a comparison of soil erosion by treatment type will be made, and relationships between sediment yield and parameters such as precipitation, soil type, and infiltration capacity will be explored.

Le but du travail est de déterminer le rapport qui existe entre la récolte soumise à des conditions de biomasse et le rendement en sédiments. On a choisi un site dans la zone biogéoclimatique peuplée de cèdres rouges de l'Ouest et de pruches de l'Ouest située dans la région centrale intérieure de la Colombie-Britannique. Le site a été récolté au cours de l'automne et l'hivers 1987/1988 à l'aide de débusqueuses munies de pneus en caoutchouc. Trois traitements ont été établis, soit des traitements correspondant à des conditions classiques, à des conditions de biomasse et à l'absence de récolte. Pour chaque traitement, trois parcelles ont été aménagées en zones de "mini-drainage" dont les limites correspondaient le plus possible à des discontinuités topographiques naturelles. Une débusqueuse a été utilisée pour enlever une quantité supplémentaire de matière ligneuse sur les trois parcelles à des conditions de biomasse.

Après la récolte, on a examiné le sol pour déterminer dans quelle mesure il avait été perturbé. Les résultats indiquent que, en moyenne, les parcelles à des conditions de biomasse étaient perturbées à 63% par rapport à 47% pour les

parcelles à des conditions classiques. Les parcelles à biomasse avaient 6% de plus en gouges profondes (de 5 à 25 cm) et 10% de plus en gouges très profondes (> 25 cm) à comparer aux parcelles classiques. Des barrages de sédiments ont été érigés le long de la limite à la base de chaque parcelle. Des tiges enfoncées dans le sol et disposées en réseau devant les barrages permettront de mesurer la quantité de sédiments déposée en function du temps. Trois ponts d'érosion aménagés à des endroits représentatifs dans chaque parcelle permettront de mesurer la quantité nette qui y est éliminée par érosion ou déposée.

Une station climatologique a été installée sur le site; celle-ci permettra de mesurer en continu les précipitations, la température de l'air et du sol, l'humidité relative, la vitesse du vent et l'ensoleillement. À ce jour, la maximum intensité de la pluviosité pour une duration de 15 minutes a atteint 5,2 mm (octobre, 1988). À titre de traitement de préparation du site, on effectuera, en 1989, un brûlage opérationnel avant la plantation. L'étude prévoit donc une période de pré-brûlage et de post-brûlage et fournira l'occasion de comparer les effets du pré- et du post-brûlage sur l'érosion du sol. À l'aide d'un simulateur de pluie, on déterminera la capacité d'infiltration sur toutes les parcelles au cours de l'été 1989. On pourra ainsi définir quels types de traitement/perturbation du sol sont suceptibles à la force d'érosion de l'eau. Les résultats permettront, entre autres, de comparer la perturbation du sol et l'érosion en surface entre les traitements. Dans la mesure du possible, on effectuera des analyses pour déterminer le rapport qui existe entre le rendement en sédiments et des paramètres comme les précipitations, le type du sol, la capacité d'infiltration, etc.

INTRODUCTION

Many of the biomass harvesting studies conducted in British Columbia to date have concentrated on the economics of, and the operational techniques available to recover woody biomass beyond conventional harvest levels. In addition to such concerns, the ENergy from the FORest (ENFOR) program is involved with determining the impact of biomass harvesting on environmental resources and values. Recently, Standish et al. (1988) conducted a review which delineated the impacts of forest harvesting on the physical properties of soils (with reference to increased biomass recovery). However, site specific field oriented research in this area is largely lacking. Forest harvesting conducted with ground based systems (eg., rubber tired skidders) can result in soil disturbance in the form of soil displacement, scalping of surface organic layers, soil compaction, etc. Such site changes can lead to localized reductions in the infiltration capacity of the soil and, potentially, an increase in overland flow and surface soil erosion. Biomass harvesting could accentuate this problem by resulting in a greater extent and severity of soil disturbance. This study was developed to assess the impact of increased biomass recovery on soil disturbance and surface soil erosion on a site harvested with a ground-based system. The specific objectives of the study are:

1. To determine the degree to which increased wood recovery would lead to a reduction in the ability of soils to resist surface soil erosion.

2. To determine the amount of surface soil erosion that can be attributed to a reduction in surface soil protection (in the form of humus, slash and logs) due to biomass harvesting.

RESULTS

Site and Study Description

The study area is located on the south side of the Seller Creek valley which is situated in the Central Interior of British Columbia (lat. 51°41' long. 121°21'). The study area is entirely within the Interior Cedar Hemlock (ICH) Biogeoclimatic Zone (but near the transition to the Englemann Spruce-Subalpine Fir zone) (B.C. Ministry of Forests 1988) and is primarily forested with Englemann spruce, subalpine fir, and scattered lodgepole pine. The relatively high elevation (1220 meters) ensures that much of the annual precipitation (total annual precipitation at a nearby station is 700 mm) is in the form of snow which usually stays on the ground from November to April. Slope gradients range from approximately 20 to 50%.

The area is characterized by deep (> 1 meter), loam to silt loam, moderately well to imperfectly drained Brunisolic and Luvisolic soils. Soil parent materials are characteristically glacial till and weathered colluvium overlying shales and siltstones. Soil samples were collected from the A and B horizons at each of the plot locations and analysed for particle size distribution. The results (Table 1) indicate that coarse fragment (> 2 mm) content varies from approximately 25 to 55% whereas the percentage of clay within the fine fraction (< 2 mm) ranges from 9 to 12%. Percentage organic matter for these soils ranges from 3.3 to 6.5% in the A horizon, and from 2.3 to 4.9% in the B horizon.

The study area was conventionally harvested with rubber tired skidders during the fall/winter of 1987/1988. Three plots were established on each of three treatments (biomass harvest, conventional

Table 1. Soil Particle Size Analysis

		Coarse Fraction (> 2mm)%	Fine Fraction (< 2 mm) % Sand	% Silt	% Clay	Classification
Biomass Harvest						
Plot	Horizon					
1	A	40.2	40.0	48.8	11.2	Loam
1	B	38.0	42.3	48.1	9.6	Loam
2	A	35.2	35.5	53.4	11.1	Silty Loam
2	B	35.6	35.4	55.6	9.0	Silty Loam
3	A	34.5	32.6	56.4	11.0	Silty Loam
3	B	34.7	36.8	53.0	10.2	Silty Loam
Conventional Harvest						
1	A	36.4	37.8	50.2	12.0	Silty Loam (to L)
1	B	36.2	38.0	49.4	12.6	Loam (to SiL)
2	A	55.4	47.0	43.8	9.2	Loam
2	B	38.6	40.5	50.7	8.8	Silty Loam (to L)
3	A	29.5	35.0	56.0	9.0	Silty Loam
3	B	28.0	34.8	56.0	9.2	Silty Loam
Unharvested Control						
1	A	39.6	39.5	51.2	9.3	Silty Loam (to L)
1	B	33.0	38.3	49.9	11.8	Loam (to SiL)
2	A	39.7	39.6	50.8	9.6	Silty Loam (to L)
2	B	34.5	37.7	50.1	12.2	Silty Loam to Loam
3	A	25.0	35.7	54.8	9.5	Silty Loam
3	B	23.0	35.0	56.7	9.3	Silty Loam
Parent Material						
3	C	25.7	28.6	54.2	17.2	Silty Loam

harvest, and control) on sites which display similar characteristics such as slope gradient, aspect, elevation, soil type and depth, and moisture regime. The nine plots, which range in size from 0.05 to 0.19 hectare, were selected as mini-basins having topographic features that largely define and control drainage into the plots. A rubber tired skidder was employed to remove a further amount of woody material from the biomass plots. On average, 30 m^3 of wood was additionally removed from each plot, which, on an area basis, represents approximately 171 m^3/hectare.

Climatic and infiltration measurements

A climate station and data micrologger were installed at the site to obtain a continuous measure of precipitation, temperature (air and soil), solar radiation, wind speed and relative humidity. Precipitation is considered the most important climatic parameter in this study because of its direct potential effect on surface soil erosion. Rainfall values for the period Sept. 23 to Nov. 14, 1988 are presented here. The total rainfall for this period was 94 mm, and appreciable precipitation was recorded on 24 out of 53 days. The highest rainfall intensity observed for this time period was a 15-minute intensity of 5.2 mm (October 13), which probably has a return period of one year or less. Total daily rainfall was found to rarely exceed 10 mm/day during this period. The water depth equivalence of the snow pack will be measured in early spring, and will provide a measure of the potential erosive energy of melting snow.

A field portable rainfall simulator, presently under construction, will be employed to conduct infiltration capacity experiments during the summer of 1989. Infiltration capacity tests will be conducted by treatment type (biomass, conventional, and control) and disturbance type (eg., skid trail, disturbed other, and undisturbed). The number of replicates will depend on the variability in soil

type, surface conditions and vegetation characteristics encountered in the field.

Soil Disturbance Survey

A soil disturbance survey was conducted on the biomass and conventional plots (the control plots exhibited no disturbance) utilizing a point-intercept technique (Smith and Wass 1976, 1988). The survey consisted of two transects per plot with point measurements taken every three meters. Soil disturbance was classified by type of disturbance (gouge, deposit or mixture) in three depth classes (shallow < 5 cm; deep 5 to 25 cm; and very deep > 25 cm), and by cause of disturbance (skid road, skid trail and other). Skid roads are bladed structures which have a well defined cut bank, running surface and berm, whereas skid trails are the result of repeated passes along the same location which can result in disrupted humus layers, exposure of mineral soil or rutting. A nuclear densiometer was used to obtain bulk density and soil moisture values at 20-meter intervals along the transects.

A summary of the soil disturbance results is presented in Table 2. The table indicates that the biomass plots have a greater coverage in skid trails compared to the conventional plots (44 vs 34%) and considerably less undisturbed ground (37 vs 53%). However, it should be noted that part of the reason for this higher percentage disturbance on the biomass plots is that skid roads were located on 2 of these plots whereas no skid roads were found on the conventional plots. In terms of specific types of disturbance, the biomass plots showed more deep and very deep gouges (8 and 10%, respectively, vs 2 and 0%), and more deep deposits (6 vs 0%) as compared to the conventional plots. The biomass plots showed correspondingly less shallow gouges (10 vs 23%). The nuclear densiometer results indicate that soil bulk densities range from 0.5 to 1.4 Mg/m^3 and that the higher density values occur on skid roads and skid trails. The soil moisture values (nuclear densiometer), obtained in late summer/early fall, are generally high (> 50% by mass) as might be expected on middle to lower slope positions in the Interior Cedar Hemlock zone.

Soil Erosion Measurement

Quantification of soil erosion by treatment type will be achieved utilizing two techniques: geotextile fabric dams, and erosion bridges. A fabric dam was constructed along the contour at the base of each of the nine plots, according to the methods outlined by Dissmeyer (1982). The dams consist of a rot-resistant, needle punched water permeable geotextile fabric affixed to a treated wood structure (Figure 1). The dams are approximately 1 meter high and vary in length from 8 to 10 meters. Erosion measurement pins were

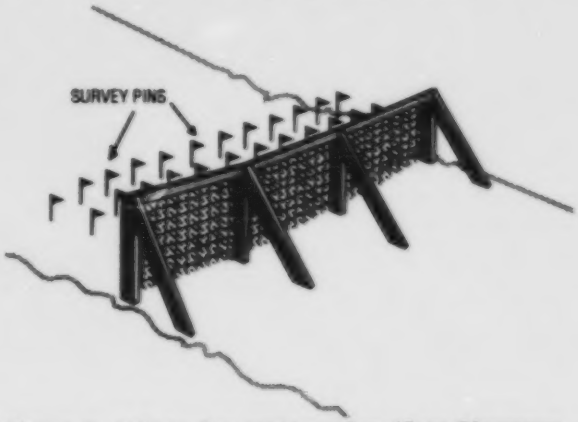

Figure 1. Fabric dam construction (from Dissmeyer 1982).

placed in front of the dams in three rows and will be resurveyed with time to determine the amount of deposited material. A total of three erosion bridges (Blaney and Warrington 1983) were installed on each plot to obtain soil erosion/deposition measurements at other locations within the plots.

Table 2. Soil Disturbance Survey Results

	Percentage Cover by			
Plot number	Skid roads	Skid trails	Other	Undisturbed
Biomass 1	0	43	11	45
2	15	45	0	39
3	21	41	9	28
Average	12	44	7	37
Conventional 1	0	26	20	53
2	0	34	0	66
3	0	43	16	40
Average	0	34	13	53

Note: Other refers to mineral soil exposed by log butt gouges and erosion. Totals across columns may not add up to 100% due to rounding errors.

The erosion bridges consist of metal rods driven into the ground onto which a predrilled carpenter's level is installed (Figure 2). Measurements are made at 5 cm intervals (total of 12 measuring points per bridge) by inserting a small diameter metal rod into predrilled holes along the level.

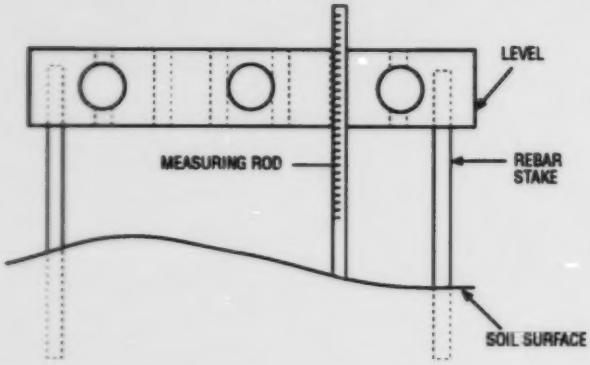

Figure 2. Schematic representation of erosion bridge (from Blaney and Warrington 1983).

The distance the rod protrudes above the level is measured and the change in distance with time represents the net deposition or erosion at that point. Soil erosion measurements will be made in 1989, both before and after an operational prescribed fire is conducted on the site. This will provide valuable insight into the fire effects on soil erosion and of the changes in soil protection afforded by slash and organic matter.

DISCUSSION

The soil disturbance survey results indicate that biomass harvesting, conducted through additional ground skidding to recover woody residues, can be expected to lead to a greater extent and degree of soil disturbance in the form of soil compaction, scalping of surface layers and gouging to greater depths. An increase in the percentage of bare mineral soil is expected to potentially result in an increase in surface soil erosion. As previously mentioned, pre- and post-fire soil erosion measurements will be made during 1989 and will provide the information with which to assess the treatment effects. In addition, the rainfall simulation experiments will provide a measure of the change in soil infiltration capacity that has occurred as a result of conventional and biomass harvest activities.

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PEATLAND DRAINAGE TRIALS IN NEWFOUNDLAND

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The peat deposits of Newfoundland have the potential to supply a portion of the island's energy needs, especially in those areas of the province where there is no other viable biomass supply. However, this potential remains under-utilized, due to drainage problems as well as poor natural drying conditions. A three-year project with the following major objectives began in 1986:

- to evaluate, through a series of field trials, modified drainage systems (5, 10, and 20 meters ditched fields),
- to evaluate the effects of the various drainage methods on the drying cycle of peat sods, and
- to evaluate the effect of rainfall over time on the water table levels, and the moisture content of the in situ peat of the various width fields.

Two different sites were chosen for the drainage trials: the first, a blanket bog on the southern Avalon Peninsula; the second, a slope bog complex in the central region of the Avalon. The peat stratigraphy is quite different at the two sites, thus providing interesting comparisons of the drainage characteristics of different peat types. Data analysis is now under way and the final report is due for completion in May 1989.

Les dépôts de tourbe de Terre-Neuve pourraient répondre en partie aux besoins d'énergie de l'Île, particulièrement dans les régions de la province où il n'existe aucune autre source viable de biomasse. Toutefois, ce potentiel reste sous-utilisé en raison de problèmes de drainage et de mauvaises conditions naturelles de séchage. On a entrepris en 1986 un projet triennal dont les principaux objectifs sont les suivants:

- évaluation d'une série d'essais sur le terrain portant sur des systèmes de drainage modifiés (champs de 5, 10 et 20 mètres de large avec fossés),
- évaluation des effets des diverses méthodes de drainage sur le cycle de séchage des mottes de tourbe et
- évaluation de l'effet des pluies en fonction du temps sur les niveaux de la nappe phréatique et de la teneur en humidité de la tourbe provenant de champs de diverses largeurs.

Deux sites différents ont été choisis pour les essais de drainage: le premier était un sol tourbeux situé dans le sud de la presq'île Avalon; le deuxième, un complexe tourbeux en pente situé dans la région centrale de la presqu'île Avalon. La stratigraphie de la tourbe est assez différente aux deux endroits, ce qui permet des comparaisons intéressantes des caractéristiques de drainage de différents types de tourbe. L'analyse des données est en cours. Des tableaux illustrent le type d'information que contiendra le rapport final qu'on prévoit terminer en mai 1989.

INTRODUCTION

The peat deposits of Newfoundland have the potential to supply a portion of the island's energy needs, especially in those areas of the province where there is no other viable biomass supply. The potential remains under-utilized, due to drainage problems as well as difficulty with drying the fuel peat. To take advantage of this indigenous fuel source, these problems must be overcome enabling rural communities to move closer to the goal of energy self-sufficiency.

With this in mind, a three year project began in 1986 to conduct drainage trials and

experiment with peat sod drying techniques. This project was jointly sponsored by:

Energy, Mines and Resources Canada
Renewable Energy Branch
Bioenergy Development Program
Ottawa, Ontario (70%)

Department of Mines and Energy,
Newfoundland
Energy Branch
Energy Demonstration and Development
Section
St. John's, Newfoundland (30%)

THE RESOURCE

The island of Newfoundland has vast areas of peat deposits. The results of a six year inventory are shown in Figure 1. Figure 2 shows the areas of fuel peat reserves in Newfoundland.

To date, the energy potential of the peatland resource has been under-utilized. Since the early 80's there have been two fuel peat demonstration projects undertaken. Brief summaries of these projects are provided.

NEWFOUNDLAND
PEATLAND INVENTORY SUMMARY

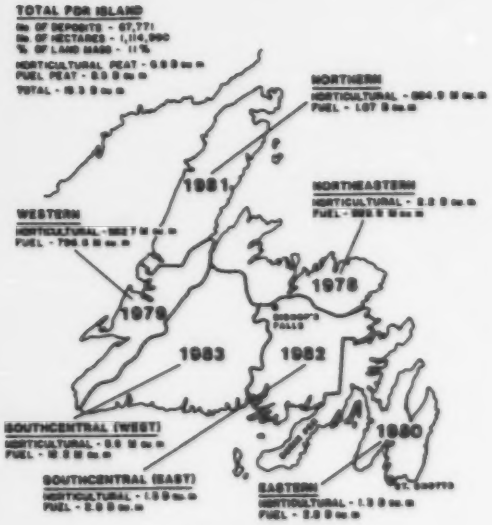


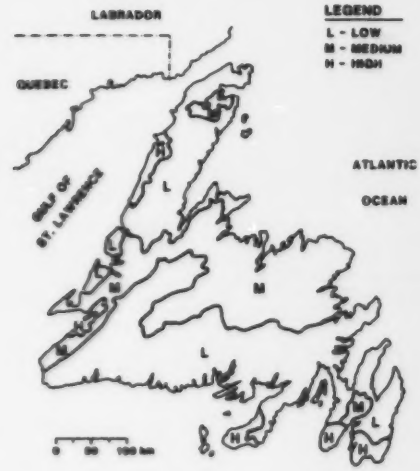
Figure 1

Bishop's Falls Milled Fuel Peat Mining Project

Between 1979 and 1982, the feasibility and viability of milled fuel peat mining were investigated. Both the Haku and vacuum harvesting systems were used. The mining operation and burning were successful, and production cost figures were developed.

Peat costs $6.00 to $7.00 per tonne at the stockpile, excluding overhead and development costs. One tonne replaced 162 L (1.02 barrels) of Bunker "C" at $30/bbl, or better than 1.4 bbl if the moisture content was kept low. A

AREAS OF FUEL PEAT
RESERVES IN NEWFOUNDLAND



SOURCE : WELLS AND VARDY, 1981

Figure 2

cash flow model revealed that, even so, the return on investment was too low to make a commercial operation viable, given the high capital and bog development costs. The current status of the project is that milled peat is produced for an oil absorbent product.

St. Shotts' Sod Fuel Peat Demonstration Project

This Project began in 1982 and is ongoing. The primary objective is to demonstrate the technical and economic feasibility of producing sod peat fuel from the blanket bogs of the Southern Avalon Peninsula.

To date a 30 hectare site has been ditched and drained. Using a Herbst sod peat extruder, pulled by a tracked, 75hp tractor it has been successfully demonstrated that the extruding process is technically feasible. However, there have been problems with the mechanical harvesting of the extruded peat sods due to wet fields. As a result uneconomic manual harvesting methods have been employed in order to produce peat sods for trial marketing. Since 1987 a field press has been used to extrude peat on drier ground away from the fields.

DRAINAGE PROBLEMS

Monitoring of the Sod Peat Project has shown that even after 4 years of drainage, the peat fields are too wet and soft to allow successful mechanical harvesting of sod peat. The soft wet fields are thought to result from a combination of inadequate drainage and severe climatic conditions.

As a direct result of the wet fields and climatic conditions at St. Shotts, the time required to dry the sod peat to a moisture content of 40% is much longer than in other areas (for example, 100 days as compared with 40 days in Ireland). This has been shortened to 50-60 days with extrusion on a dry mineral ridge with a field press.

The following figure clearly illustrates the problems encountered at St. Shotts. (Figure 3).

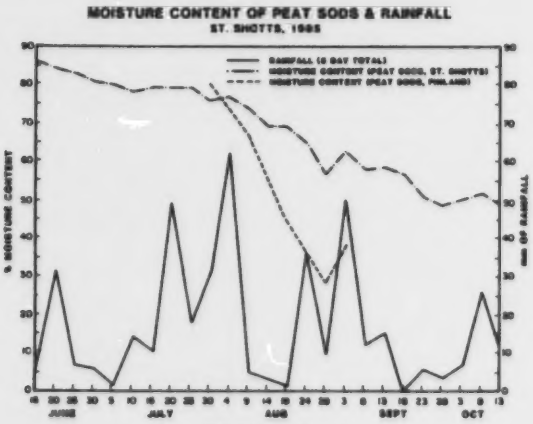


Figure 3

In analyzing the results of this project, it has become evident that additional research is necessary in the areas of drainage and drying of peat. The sod peat project has suffered and continues to suffer from wet fields - a clear indication that the present drainage plans are not adequate. The climatic environment in this area of the province is severe; excessive rainfall and low number of direct sunshine hours. This, combined with the fact that Newfoundland oceanic peats are low in hydraulic conductivity (ca 1 x 10^{-5} cm/sec vertical, 8 x 10^{-5} cm/sec lateral) (Rayment and Campbell 1980) indicates that extreme drainage measures are necessary.

DRAINAGE TRIALS

A three year project conducting drainage trials and testing peat sod drying techniques for sod peat harvesting in Newfoundland began in the summer of 1986.

The objectives of this project are as follows:

- to evaluate the present 20 metre ditched field system being used in the St. Shotts project by shutting down production on a few fields and monitoring the drainage;
- to evaluate, through a series of field trials, modified drainage systems (20, 10 and 5 metre ditched fields) together with combinations of surface conditions;
- to evaluate through a series of field trials the effect of the various drainage methods on the drying cycle of extruded peat sods;
- to do cost evaluations of the various drainage systems as to their costs and production effectiveness in a commercial peat harvesting operation;
- to demonstrate through effective applied research the limitations and feasibility of conventional and modified sod peat production systems under Newfoundland climatic conditions; and
- in general, to help solve the current problems associated with sod peat harvesting in Newfoundland, so that this indigenous fuel source can be utilized to help achieve the goal of energy self-sufficiency.

YEAR 1 (1986-87)

An 8 hectare peatland site was chosen adjacent to a Sod Peat Harvesting Project near St. Shotts on the southern tip of the Avalon Peninsula. This site was surveyed and ditched utilizing a drainage plan (Monenco Consultants Limited were subcontracted to assist with the plan) consisting of a successive pattern of 5, 10 and 20 metre spaced ditches (see Figure 4). The ditches were cut to a depth of 1 m. Perforated stand pipes were installed in the various fields to monitor water table draw down over time. A sampling program was initiated whereby peat sod samples and surface layer samples (10, 20, 30 cm) were taken and analyzed for moisture content.

YEAR 2 (1987-88)

A second site was chosen (5 ha) at Markland near Whitbourne, Newfoundland. This site was ditched in the fall of 1987 and some preliminary stand pipes were installed. The site was chosen for its different peat type and depth, as well as for its location in a much less severe climatic zone (see Figure 5).

The continuation of water table measurements and sampling at St. Shotts was carried out through 1987-88.

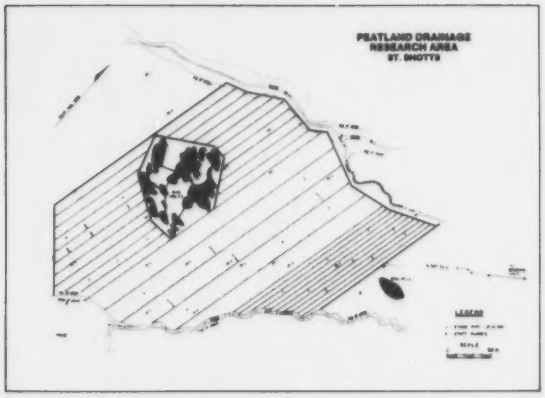


Figure 4

YEAR 3 (1988-89)

The Markland site was fully instrumented with stand pipes and data collection was expanded to include Markland and St. Shotts. Data was collected throughout the field season (May - October). Analysis of the data was carried out during the fall and winter.

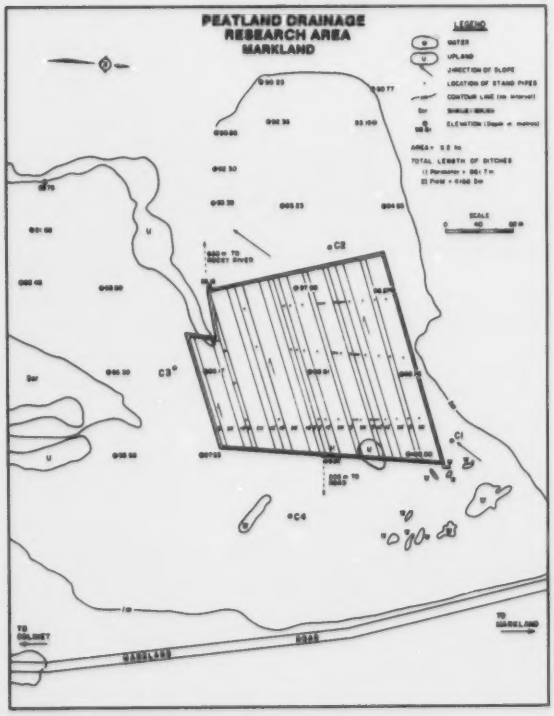


Figure 5

BEARING CAPACITY TRIALS

In 1987-88 preliminary trials were carried out at St. Shotts and Markland investigating the load-bearing capacity of peatlands. This work was carried out in conjunction with staff from the Civil Engineering Department of the University of New Brunswick. The objective of this work was to assess whether there is any relationship between water table, moisture content, peat type and depth to bearing capacity and trafficability on peatlands. These preliminary tests resulted in sufficient interest by both the federal and provincial Energy Departments to commission a second study designed to investigate the bearing capacity of peat soils as it relates to development for fuel production (1988-1991).

During 1988 intensive testing was carried out at the Markland and St. Shotts drainage sites. Plate load, shear plate, tire and pull tests were carried out on partially drained and undrained sites. Pore pressures were measured in conjunction with the tests to determine the effect of a high water table on the peat. Although the results to date are insufficient to draw conclusions, some patterns have been identified and it is strongly felt by the investigators that a definite relationship between water table moisture content and bearing capacity will emerge.

RESULTS

The following table presents the average water table levels on a seasonal basis (June-Sept.) achieved on the various width fields after two years of drainage at the St. Shotts site and one year at the Markland site. It can be seen from the table that during 1987 the water table draw down at St. Shotts was initially great and one year later in 1988 the water table levels were rising: this is attributable to the fact that 1987 was an extremely dry year and rainfall during 1988 was more normal.

WATER TABLE DATA
DISTANCE BELOW SURFACE (cm)

	ST. SHOTTS 1987			ST. SHOTTS 1988			MARKLAND 1988		
	5m	10m	20m	5m	10m	20m	5m	10m	20m
AVERAGE	57	55	36	52	33	16	48	30	23
MINIMUM	27	28	22	37	20	8	24	23	7
MAXIMUM	78	71	54	78	49	30	59	54	37

Values are for the operational period June-Sept.

DISCUSSION

Water Table Levels

The hydrological data indicate that the blanket bog at the St. Shotts site responded to drainage and that the magnitude of change was directly related to the ditch spacing. The water table measured in wells centered between ditches on the 10 and 5 metre fields was typically 10 - 30 cm and 30 - 50 cm respectively, lower than in the undrained control site (see Figure 6). A 20 meter ditch spacing

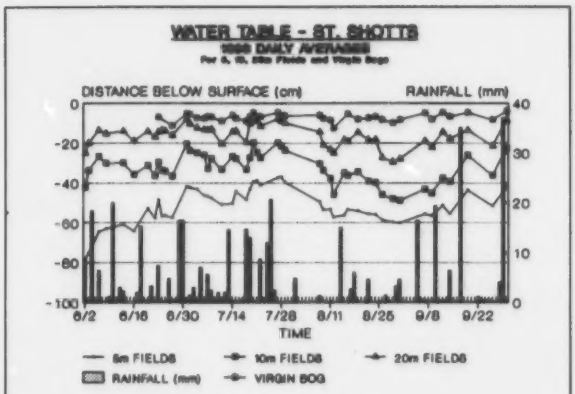


Figure 6

produced only a minor change when compared to the undrained condition. However in 1987 as can be seen from the data in Table 1, a greater change was recorded and is attributable to the below normal rainfall levels and extremely dry conditions of that year. The initial draw down near the ditches in all fields resulted in the water table being well below the acrotelm (the active hydrological layer) resulting in low transmissivity on all sites. It is evident from the data that only near the vicinity of the ditches was the hydraulic gradient sufficient to produce drainage and that, at this time, at the St. Shotts site two years after ditching only the 5 meter fields are being effectively drained. Additional data is needed to see if this trend will continue.

Moisture Content

The moisture content of the in situ peat at the 20-30 cm depth was 88.3% in the undrained state, and fell to 85.5% and 84.8% after one and two years of drainage respectively. On the 20 metre field the moisture content decreased with depth as was the case on the undrained sites and is partially attributable to the increased density of the peat. With 5 metre spacing, the lower water table has drained the 0-10 cm layer resulting in a decrease in moisture content toward the surface. At the 20-30 cm depth a similar moisture content was measured on the 5, 10, and 20 metre fields. This demonstrated the high water retention capacity of peat below the acrotelm. Although the water table in the 5 m fields is low, little actual water loss has occurred in the 20-30 cm layer.

Conclusion

It is obvious from the data that, with only two years of data from the St. Shotts site and one year from the Markland site, monitoring of these sites must continue to produce the data base that is necessary to establish drainage characteristics of the peat deposits of Newfoundland.

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ENERGY FOREST R & D IN NEWFOUNDLAND: 1981-88

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Government policies advocating biomass as an energy source indicate the need for a sustained fuelwood management program. However major constraints in developing a stable, long-term biomass fuel industry throughout much of Canada are shortfalls in biomass reserves due to overcutting, especially in climatically sensitive regions noted for slow growth rates and the eventual depletion of 'green junk' reserves.

To address these and other fundamental problems associated with creating and maintaining productive fuelwood forests in the boreal forest region an energy plantation research and development project was initiated in Newfoundland in 1981. The project is funded by ENFOR (ENergy from the FORest) Program. The article reviews the progress and achievements form 1981 to 1988 including studies in biomass productivity, biometeorology, and economic assessments.

Les politiques gouvernementales qui préconisent l'exploitation de la biomasse en tant que source d'énergie soulignent également la nécessité d'un programme soutenu de gestion du bois à brûler. Toutefois, des pénuries dans les réserves biomassiques, dues à des coupes trop importantes, particulièrement dans les régions sensibles au climat qui sont caractérisées par une croissance lente, et l'épuisement ultime des réserves de verdure, sont les principales contraintes liées au développement à long terme d'une industrie stable des combustibles biomassiques.

Pour résoudre ces problèmes et d'autres difficultés liées à la création et au maintien de forêts productives, destinées à la production de bois à brûler, dans la région de la forêt boréale, on a entrepris en 1981 à Terre-Neuve, un projet de recherche et de développement sur l'énergie fournie par les plantations. Ce projet est subventionné dans le cadre du programme ENFOR (ÉNergie de la FORêt). Dans la présente communication, on décrit les progrès et les résultats obtenus entre 1981 et 1988, notamment ceux qui découlent d'études de productivité de la biomasse, de biométéorologie et d'évaluations économiques.

INTRODUCTION

In Newfoundland, wood meets approximately 25% of the residential energy needs. Through the Canada-Newfoundland Renewable Energy Demonstration Agreement (CNEDA) and industrial initiatives new institutional and industrial wood burning boilers will require approximately 250 000 t a^{-1} by 1990 (Fletcher and Robertson 1989). In addition, there are approximately another 150 boiler plants which could be converted to fuelwood feedstock. Such a conversion would increase the demand for wood to 2.5 million tonnes per year.

The ability of forests in some parts of Newfoundland to sustain a high level of biomass utilisation is questionable. For example, on the Avalon Peninsula, where the demand for fuelwood is highest, the annual allowable cut (AAC) is 112 000 m^3; yet in 1983, the fuelwood consumption alone was 196 000 m^3 (Northlands 1984). Also, throughout Newfoundland the forest has deteriorated to a patchwork of immature stands which cannot meet future fuelwood demand due to the longer rotation age required for coniferous forests to reach a merchantable volume (Wilton 1984). Therefore, there is a need to introduce short-rotation, high-yielding energy plantations wherever possible to increase forest productivity to meet both fuelwood and industrial wood demand in the future.

To complement governmental and industrial programs promoting wood as a renewable energy source, an experimental energy forest project was initiated by Forestry Canada, Newfoundland & Labrador Region in 1981 with funding from ENFOR. This paper summarises the results of studies within this project.

GROWING STOCK

The genus Salix was chosen as the basic biofuel growing stock because extensive experiments in Sweden and Finland in the mid-1970s demonstrated that selected clones and hybrids yielded growth rates 10-20 times that normally found in the boreal forest (Siren 1979; Pohjonen 1980). Throughout temperate Europe Salix has been cultivated for centuries for fuel, crafts and planted for shelterbelts and flood control (Robertson 1984a).

Beginning in 1980 the author began collecting superior Salix clones throughout Europe and eastern North America. To date more than 200 clones have been collected. Of these, clones from Europe mostly with some Salix viminalis in their parentage, have by far performed the best.

Table 1 compares the average height growth of selected clones in experimental plots in three locations across Newfoundland. Each site represents three contrasting climatic regions. Pasadena nursery in western Newfoundland is the superior site with deep, fertile sandy loam soils and a sheltered climate. By contrast, Mt. Pearl site in eastern Newfoundland has a cool, windy climate and the soils are shallow and stony. The Red Cliff site in central Newfoundland has deep sandy loam soils and a drier and more continental climate than Pasadena and was not as intensively managed. Even on the poorest sites with the least management intensity, Salix yields were between 15-20 times the normal yield for boreal forest (0.5 - 1.5 t $ha^{-1}a^{-1}$).

Table 1. Average Height and Diameter of Some Salix Clones in Plots at Pasadena, Grand Falls and Mount Pearl, Newfoundland.

Clone No.	Taxa	Mean Height (m)	Mean DBH* (cm)	Age (yrs)
	MOUNT PEARL			
3040	S. myrsinifolia v. cotinifolia	4.00	4.45	4
3202	S. amygdalina cv DIVACEA	4.00	4.19	4
3048	S. purpurea	3.61	3.00	4
3049	S. miyabiana	4.26	4.65	4
3200	S. viminalis (BOWLE'S hybrid)	3.79	2.95	4
3205	S. viminalis cv BROWN MERIAM	4.08	4.11	4
3213	S. viminalis x caprea HARD OSIER	4.32	4.72	4
3215	S. viminalis x caprea x cinerea (COLES)	3.99	4.39	4
3217	S. viminalis x caprea x cinerea (DASYCLADOS)	3.39	3.10	4
3219	S. x stipularis	3.94	3.58	4
3222	S. viminalis x cinerea (REIFENWIND)	4.02	4.70	4

.../Cont'd.

Table 1. (Concl'd.)

Clone Iona	Taxa	Mean Height (m)	Mean DBH* (cm)	Age (yrs)
	GRAND FALLS			
3048	S. purpurea	3.40	3.36	3
3049	S. miyabiana	3.54	4.91	3
3202	S. amydalina cv DIVACEA	3.48	4.00	3
3205	S. viminalis cv BROWN MERIAM	3.42	3.08	3
3216	S. x callodendron	3.16	4.61	3
3219	S. x stipularis	3.11	4.44	3
	PASADENA			
3215	S. viminalis x caprea x cinerea (COLES)	3.47	2.98	2
3200	S. viminalis (BOWLE'S hybrid)	[illegible].53	2.42	2
3002	S. viminalis cv ELEGANTISSIMA	5.05	3.04	2
5017	S. alba (Italy 13/59)	4.01	3.39	2
3219	S. x stipularis	3.34	2.08	2
3222	S. viminalis x cinerea (REIFENWIND)	3.25	2.62	2
3205	S. viminalis cv BROWN MERIAM	2.97	2.75	2

*DBH = Diameter at stump height.

Very high stand densities of up to 35 000 stools per hectare are a major feature of high yielding Salix plantations. Table 2 summarises the total above-ground biomass and energy yield of two levels of stand densities of 3-year-old Salix under intensively managed conditions at Pasadena.

Table 2. Comparison of Yields of Selected Salix Clones Planted at Two Levels of Stand Density at Pasadena, Newfoundland.

Clone No.	Taxa	Above-Ground Yield (ha^{-1}) 35 000 stools Weight (ODT)	35 000 stools Energy (TJ)	25 000 stools Weight (ODT)	25 000 stools Energy (TJ)	Av. ht. (m)
3002	S. viminalis cv ELEGANTISSIMA	114	2.1	81	1.4	4.75
5004	S. fragilis	39	0.7	18	0.3	4.04
5002	S. nigra	9	0.2	6	0.1	3.18
	S. alba (Italy)	45	0.8	33	0.6	4.46
	S. alba (Romania)	42	0.8	30	0.5	4.10
	S. triandra	36	0.6	24	0.4	3.88
3200	S. viminalis (BOWLE'S hybrid)	33	0.6	24	0.4	3.98

One advantage of Salix plantation is our ability to coppice them frequently. Table 3 shows the productivity of 1-year old shoots on stools that have been coppiced annually for two and three years respectively.

Table 3. Productivity and Energy Value of 2- and 3-year-old Stools of Selected Willow Clones Coppiced Yearly in Early Spring Prior to Bud-Burst at Pasadena, Newfoundland (based on a density of 30 000 stools/ha^{-1}).

Species	Clone No.	Annual Yield (ha^{-1}) 2nd year stools ODT	2nd year stools GJ	3rd year stools ODT	3rd year stools GJ
Salix viminalis	082	13.4	241	28.5	513
S. alba (Italy)	5016	12.9	232	20.2	364
"	5017	7.9	142	24.0	432
"	5018	7.7	139	24.4	439
"	5019	4.6	83	8.2	148
S. alba (Romania)	5020	3.3	59	12.8	230
"	5021	2.7	49	10.5	191
"	5022	2.8	50	9.8	176
"	5023	7.0	126	15.8	284
S. fragilis	5004	12.8	230	21.0	378
"	5005	8.1	146	16.5	287
"	5010	6.0	108	21.0	378
"	5011	10.6	191	18.0	324
S. nigra	5002	9.5	171	13.5	243
"	5002	9.5	171	17.0	306
"	5009	8.7	157	9.0	162

Source: Robertson 1986.

The multiple use of Salix in agroforestry for shelterbelts, fuelwood, fodder as well as a raw material for industrial processing was proposed by Robertson (1984b). This multiple-use scenario includes mixing Salix as a nurse species with fast-growing conifers such as larch to basically increase biomass productivity while diversifying the species composition. Planting experimental mixtures, with Salix and Larix, is scheduled to begin in 1989.

PLANTATION ESTABLISHMENT

Two main experimental energy forest plantations are located at Red Cliff near Grand Falls and at Salmon Pond near Glenwood in central Newfoundland.

The Red Cliff site is about 1 hectare and has deep sandy loam soils. Despite the excellent soil conditions the site was formerly part of a pasture/hay field and so grass is a particularly serious problem for the willows, although Japanese larch will undoubtedly fare much better. Abitibi-Price, the owners of the site, have planted white spruce adjacent to the energy forest plots which will be useful for comparing growth and yield. In early spring of 1986, it is noteworthy that a forest fire burned the whole site killing off an 8-year-old white spruce plantation but did not harm the Salix energy forest plots.

The Salmon Pond site was formerly a black spruce/ white birch cutover that was stripped of vegetation and humus layer for a 10 hectare experimental energy forest. Most of it has been planted with Salix over a period of three years as stock became available. The energy and radiation budget of the site has been studied intensively over a three-year period as part of a baseline biometeorological study (see below).

Smaller plantations have been established near Gander and on the Avalon Peninsula. Also, since 1988 the Research Division of the Newfoundland Department of Forestry has undertaken establishment of experimental plantations. So far, they have established six test plots, mostly in western Newfoundland and Labrador, and will be establishing several more in northern and western Newfoundland in 1989.

BIOMETEOROLOGICAL RESEARCH

The forests of Newfoundland are particularly sensitive to climate in that disturbances, exploitation and forest fires can lead to site degradation whereby vast areas can be rendered unto scrub. Restoring these areas is a difficult undertaking from a technical and economic standpoint.

The main purpose of biometeorological studies is to demonstrate that the productivity of the

boreal forest is far below what can be achieved through intensive silviculture. Furthermore, regardless of silvicultural options, there is a need to predict potential biomass production (theoretical or otherwise) of plantations before any consideration can be given to management investments.

Since energy is the basis of all life, it follows that assessing the partitioning of energy into various components, such as sensible heat, soil heat, evapotranspiration and, above all, energy stored in biomass will give a better appreciation of potential forest production. Salix, being a fast growing species and very responsive to radiation and moisture, is an ideal test crop for energy balance studies.

The keystone of biometeorological studies of energy forests is based on the energy balance/Bowen Ratio method using an automatic unit consisting of a reversing temperature difference measuring system (RTDMS) and associated sensors for net radiation, soil heat flux, heat storage, precipitation and wind profiling (McCaughey 1986, 1988; McCaughey and Robertson 1989). The methods and results of this study are described in detail by McCaughey et al. elsewhere in these proceedings.

Dowsley (1987a) assessed the gross photosynthetic rate for a Salix canopy given the estimations of incoming photosynthetically active radiation (400-700 nm) and current leaf area. The photosynthetic rate was combined with coefficients of air temperature and respiration, respectively, and the above ground/below ground biomass ratio to estimate stand growth rates.

Since the equation for estimating net photosynthetic rate requires leaf area, LA, as input, Dowsley (1987a) found that the equation

$$LA = 0.67\ H\ D$$

where H = shoot length and D = shoot basal diameter, accurately predicts leaf area.

Typically, incoming radiation reaches a maximum at 14.00 NDST under clear and partially cloudy skies (Figure 1); while under overcast skies, PAR is reduced by as much as 50% (Figure 2). On most days, between 10.00 and 18.00 hours, plants reflect about 10% of the PAR.

Dowsley (1987b) also studied the correlation of diurnal growth patterns to climate variables in a young Salix energy plantation. Of the three clones investigated, Salix viminalis was the most vigorous apparently because of its ability to continue shoot elongation later in the growing season (Figure 3). Apparently, heavy rain (20 mm in one particular week) caused basal diameter to increase dramatically (Figure 4). Height increment is highest in the late afternoon (Figure 5) when transpirational rates are lower and hence the tree is able to form assimilates. The diameter increment is highest during the night (Figure 6) which Dowsley (1987b) attributed to daily hydrostatic changes regulated by soil water content and transpirational rates.

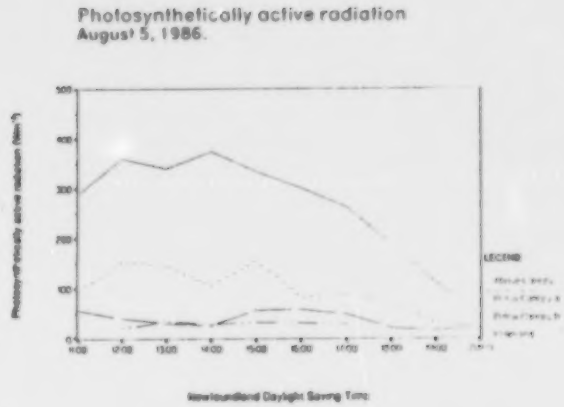

Figure 1. Photosynthetically active radiation on part of a sunny day (5 August 1986).

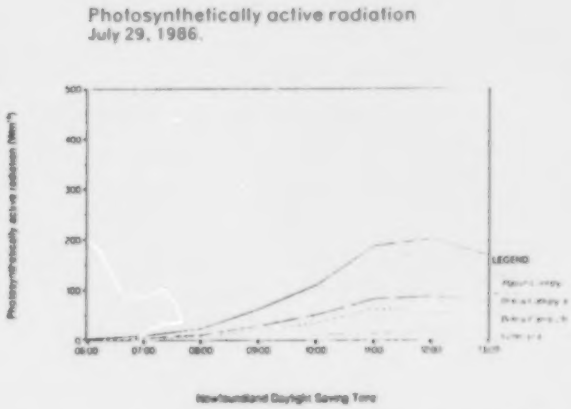

Figure 2. Photosynthetically active radiation for part of a cloudy day (29 July 1986).

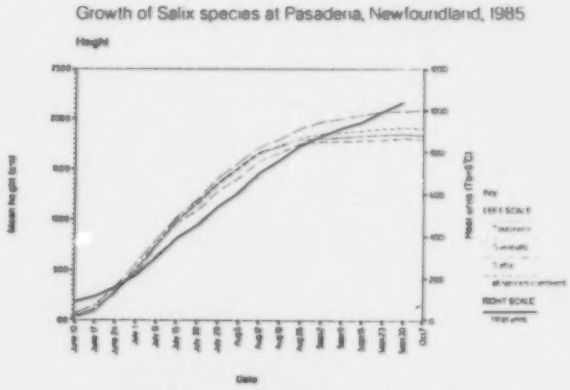

Figure 3. Height growth of Salix species at Pasadena, Newfoundland, 1985 (from Dowsley 1987b).

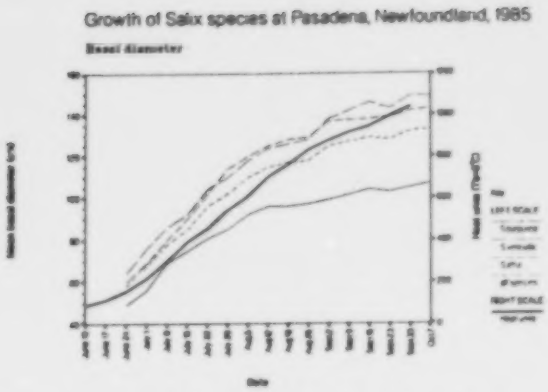

Figure 4. **Basal diameter growth of Salix species at Pasadena, Newfoundland, 1985 (from Dowsley 1987b).**

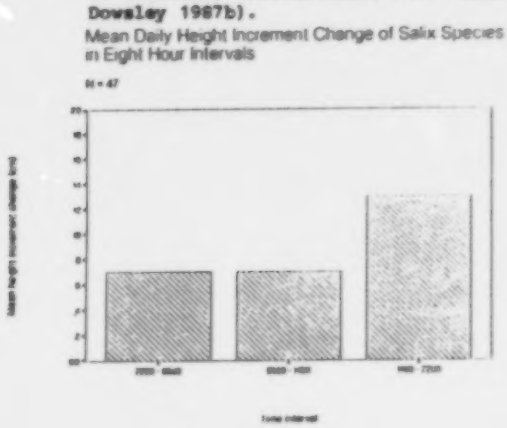

Figure 5. **Mean daily height increment change of Salix species in eight hour intervals (from Dowsley 1987b).**

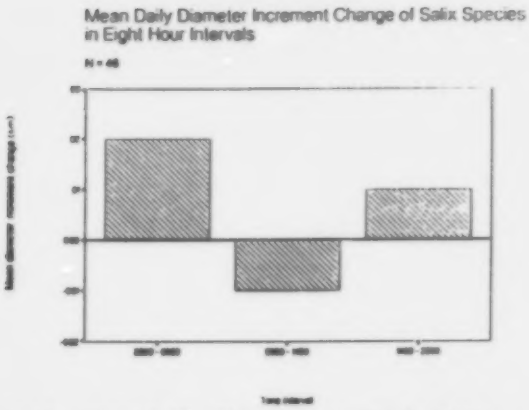

Figure 6. **Mean daily diameter increment change of Salix species in eight hour intervals (from Dowsley 1987b).**

Dyer (1983) conducted a pilot study of the feasibility of establishing Salix energy plantations in Newfoundland. This included examination of the suitability criteria of plantations taking technical, biological and socio-economic considerations into account. A series of capability maps for an area on the Avalon Peninsula in eastern Newfoundland included classification of soils and topography, vegetation cover, land use, and accessibility. The fuel requirements of potential markets throughout Newfoundland was assessed. Based on these studies, which were done without the benefit of an actual energy plantation (one was not established until 1986), Dyer concluded that though the economic viability of plantations was doubtful, the lack of accurate cost data for Newfoundland conditions made a realistic economic analysis difficult.

Fletcher (1988) examined the competitive position of fuelwood from proposed energy plantations in Newfoundland. His analysis was based on experience with plantations in Europe (particularly Sweden) and eastern North America. Also, he had the benefit of results from several years of growth and yield studies of Salix in various locations in Newfoundland from which to make a more realistic, although not definitive, economic analysis.

Based on the estimated cost of biomass from a hypothetical energy plantation in Newfoundland of \$54.00 ODT^{-1}, energy forests could compete with fuel oil as well as biomass harvested from natural forest. In fact, even if the cost of plantation biomass rose from \$54.00 to \$70.00 ODT^{-1} it would still compete with the alternatives. For more details pertaining to Fletcher's analysis see Fletcher and Robertson (1989) elsewhere in the Proceedings.

CONCLUSIONS

Growth and yield experiments show that Salix biomass productivity is phenomenal compared with the average boreal forest productivity. These results, coupled with biometeorological research, show that potential forest productivity through intensive management and species selection is at least 15-20 times what is being achieved through current practices.

Some of the benefits of energy plantations outlined by Fletcher (1988) are:

- Provision of a renewable energy feedstock which could reduce Newfoundland's dependence on imported oil.
- Provision of sustainable employment opportunities in rural areas of Newfoundland.
- Increased expenditures on local goods and services similar to those currently provided by the forestry and agricultural industry.
- Generation of government revenues through a variety of business, corporate and personal income tax.

  Stimulation of new research in forestry and biotechnology in Newfoundland.

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P2-1
THE NON-CONSOLIDATING FEEDER
ABSTRACT
DEVELOPMENT
FROZEN LUMPS REMOVAL
INTRODUCTION

A NON-CONSOLIDATING DISCHARGE FEEDER

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A novel feeder has been developed which discharges biomass from a storage system without the flow problems that are common with other systems. The feeder essentially consists of one or more slots which traverse back and forth without any relative movement or friction between the stored material and the feeder. Hence, the feeder does not compact or consolidate material. Discharge of material takes place while the slots are moving and stops when the slots are stationary. The feeder requires relatively very low power to operate and results in first-in-first-out flow. Two such feeders have been in operation for biomass materials - one at a northern B.C. pulp mill for feeding hog fuel into the boiler and another at a fish hatchery in P.E.I. for delivery of wood chips to a combustion device for plant heating. Both the feeders have performed well. Modifications have been done to one of the test feeders to remove large frozen lumps of hog fuel that occur during outside storage of the fuel in winter. The feeder will be undergoing field trials at a northern B.C. pulp mill early in January 1990.

Le nouveau système mis au point permet l'alimentation en biomasse, à partir du lieu de stockage, sans les problèmes d'écoulement fréquents avec les autres systèmes. Ce système est essentiellement constitué d'une ou plusieurs fents qui se déplacent d'avant en arrière sans mouvement relatif ni friction entre le matériau stocké et le dispositif d'alimentation. Par conséquent, il n'y a pas de compactage du matériau stocké. Le matériau est distribué lorsque les fentes sont en mouvement. Le dispositif exige relativement peu d'énergie et permet l'alimentation du matériau le plus ancien en premier. Deux systèmes sont actuellement en fonctionnement, l'un dans une papeterie dans le nord de la Colombie-Britannique sert à alimenter la chaudière en déchets de bois et l'autre dans une pisciculture se l'île-du-Prince-Édouard sert à alimenter la chaufferie en copeaux. Les deux fonctionnent trés bien. Des modifications ont été apportées à l'un des systèmes d'essai pour éliminer les amas de déchets de bois congelés qui se forment en hiver dans les tas stockés à l'extérieur. Il sera mis à l'essai en conditions réelles dans une papeterie du nord de la Colombie-Britannique au début de janvier 1990.

INTRODUCTION

The discharge feeder is the most common cause of flow problems with biomass bulk storage systems (1,2). Typical problems with existing feeders which are illustrated in Figure 1 and are as follows:

- flow takes place mainly from the rear of the bin with little or no movement of material in the front part of the bin
- compaction of material occurs in the front part of the bin

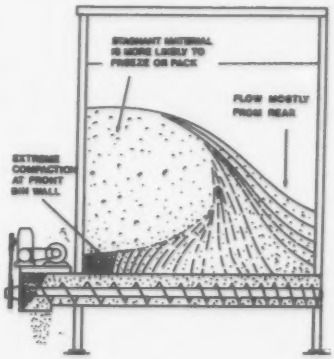


FIGURE 1 TYPICAL DISCHARGE FEEDER PROBLEMS

- the feeder requires excessive amount of power to operate and stalls often.

- stagnant material in the front part of the bin gains additional strength and is prone to freezing during cold weather.

While the above problems can be minimized to some extent with appropriate bin-feeder design, some compaction and non-uniform flow are inevitable with existing systems. Hence, these systems were felt to be limited in terms of size and length and the need for improved systems was obvious.

CONCEPT OF THE NON-CONSOLIDATING (N-C) FEEDER

The patented N-C feeder(3) (Figure 2) essentially consists of one or more slots that traverse back and forth. Discharge of material takes place through the slots while the slots are moving and stops when the slots are stationary. What makes this feeder unique is that while the slots are moving, the remainder of the feeder deck that is in contact with the stored material is stationary and as a result, there is no friction between the feeder and the stored material.

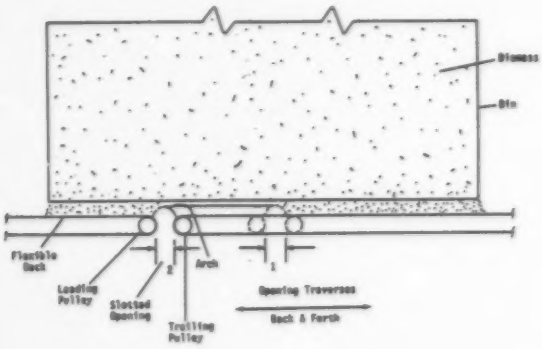


FIGURE 2 CONCEPT OF THE N-C FEEDER

The lack of friction between the feeder deck and the stored material above it eliminates any compaction or consolidation of the material. Hence, flow interruptions which are common with other feeders are avoided with the feeder and a reliable storage and feed system is achieved.

Other advantages of the feeder system are:

- flow pattern of material is first-in-first-out; this is a very desirable feature as it assures that the contents of storage are periodically renewed and material degradation or freezing of the stagnant areas is avoided.

- power required to operate the feeder is low due to the lack of friction between the stored material and the feeder. Maintenance requirements are quite low too due to the lack of friction and wear.

- the stored material can not be damaged due to feeding; even fragile materials can be handled.

DEVELOPMENT

Several pre-production feeders were designed, constructed and tested over a period of two years.

Rigid Feeder Deck

The first feeder that was built was a simple design made out of canvas sliding on a plywood deck (see Figure 3). The unit performed well even on very rough hogfuel in spite of the fact that it was feeding material out through only a 300 mm wide hopper. A drawback of this design was that the 1.2 m long feeder had an overall length of 3.6 m as the rigid support had to be "parked" on either side of the machine. This first N-C feeder proved that the concept of this feeder was sound and can provide a very reliable system.

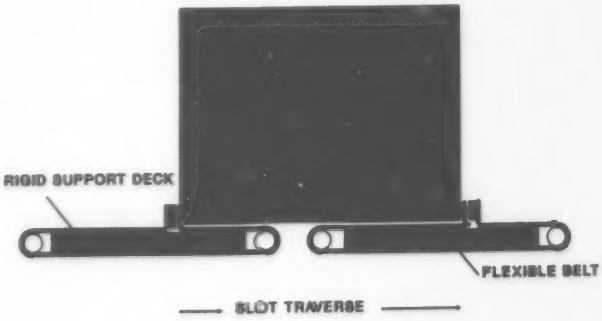


FIGURE 3 N-C FEEDER WITH A RIGID SUPPORT DECK

Partial Wrap-Up Deck

A second more elaborate unit was built out of steel (see Figure 4) which addressed the problem of the space required to park the support decks on either side of the feeder. The deck for this unit consisted of idlers which made up it flexible to allow a partial "wrap up" of the support deck. The feeder was designed for a bin outlet 1.8 m long x 0.6 m wide. Figures 5 and 6 show photographs of the feeder. This feeder was very effective in discharging a range of biomass materials (poor to free flowing) without compaction or any other flow problems.

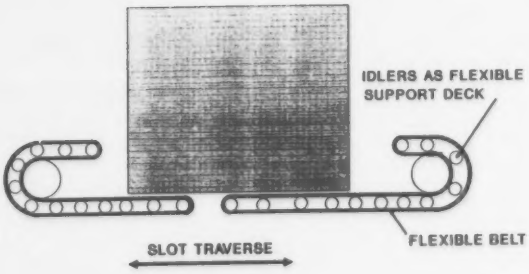


FIGURE 4 N-C FEEDER WITH A PARTIAL WRAP-UP DECK

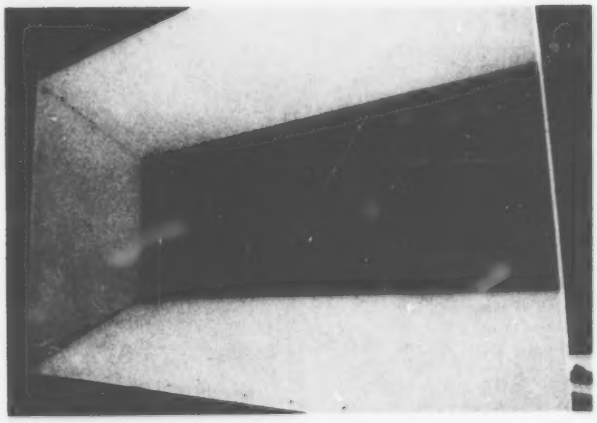


FIGURE 5 TOP VIEW OF A SINGLE SLOT TEST SYSTEM

FIGURE 6 VIEW OF DISCHARGE END OF TEST SYSTEM

Tests were also done on this unit to determine the flow rate of material as a function of traversing speed of the slot, width of slot and material characteristics. Metering ability of the slot on its own was found to be poor. This metering problem has subsequently been solved using a separate metering device below the slot to provide accurate volumetric control.

Complete Wrap-Up Deck

A third much larger feeder was designed with a complete wrap-up deck to allow the deck to be parked below the area traversed by the slot as shown in Figures 7 and 8. Material discharged at the slot was picked up by a shuttle conveyor which traversed back and forth with the slot. The feeder was designed to fit a bin outlet 1 m wide x 4.6 m long. As with the other feeder designs, this feeder worked well. The feeder was able to discharge the contents of a 80 cu. m. capacity bin very effectively without any flow problems. Mechanically, this feeder design was more complex than the two previous designs and a commissioning period was required to solve some minor problems before satisfactory operation was achieved.

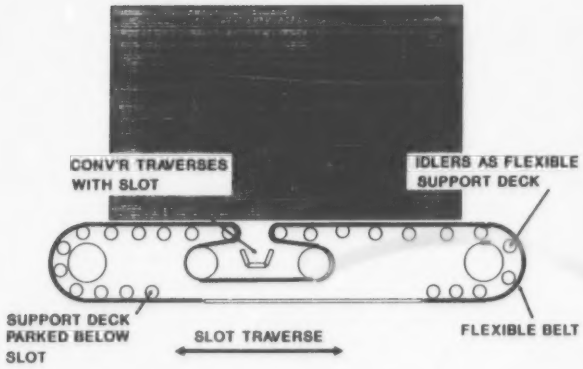


FIGURE 7 A COMPLETE WRAP-UP N-C FEEDER

FIGURE 9 PHOTOGRAPH OF FIELD SYSTEM FEEDING INTO A HOG FUEL BOILER

FIGURE 8 LARGE N-C FEEDER TEST SYSTEM

FIELD INSTALLATIONS

The first field installation of the N-C feeder was done at Northwood Pulp, Prince George, B.C., to feed hog fuel into the mill's number 4 boiler from one of five surge bins. As the feeder was discharging fuel directly into the boiler, the boiler had to be designed to withstand the occasional blow back of hot gases from the boiler. Hence, the flexible rubber belt was replaced by mass chain (see Figure 9). A two slot feeder was constructed in order to reduce its overall length. This feeder was started up in April 1988 and has worked well for over a year. Initially, some minor modifications were required to avoid the chain in the feeder deck getting caught.

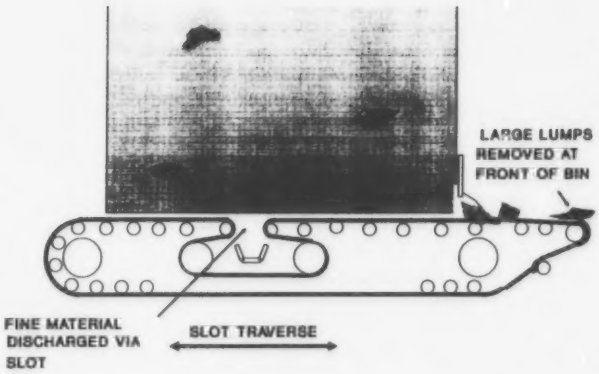
The next major installation of the feeder was at a grain terminal in Vancouver to feed grain dust out of 25 m tall silo. Grain dust is similar in its flow characteristics to sawdust and is prone to bridging with conventional feeder systems. The storage system with the N-C which was started up in September 1988 and has performed well since.

Installations of several more N-C feeder systems are currently underway, including four feeders at a new pulp in Alberta.

FROZEN LUMPS SEPARATOR

A common problem during outside storage of biomass is the presence of large frozen lumps of material during the winter months. Most discharge feeders are not capable of handling such large lumps. In the case of chain feeders, the large lumps accumulate at the front (discharge) end of the hopper, resulting in plugging of material, breakage of chains as well as damage to the front wall of the hopper. The large N-C feeder shown in Figure 8 above was modified to remove these large lumps of material.

The modifications done to the feeder are illustrated in Figure 10. A separate drive was added to one end of the feeder to allow slight advancing of the whole belt in one direction, as is done in the case of a normal belt feeder. This



motion was superimposed on the traversing motion of the slot as described earlier. Hence large lumps which did not go through the slot tended to be advanced gradually to the front end of the bin and removed separately. The advancing motion was intermittent and occurred only while the slot was near the front end of the bin, to minimize carry over of "good" material. The feeder was first tested and debugged at BC Research before it was set up at a northern BC pulp mill. Field trials are planned for the winter of 1989/90.

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P2-2
BIOMASS-FUEL-METERING EQUIPMENT
FOR SMALL-SCALE SYSTEMS
C A Short

BIOMASS-FUEL-METERING EQUIPMENT FOR SMALL-SCALE SYSTEMS

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Reliable, efficient, low-emissions operation of combustion systems fuelled with wood in particulate form requires close control of the mass flow rates of both the fuel and the combustion air. To date, all commercially-available small systems tested have incorporated a mechanism - usually an auger - which attempts to both meter and feed fuel from the storage hopper to the burner; such an approach eventually leads to erratic fuel flow and therefore loss of control of the fire either because of fuel compaction within the hopper, usually in the region of the fuel exit from the hopper, or because of jamming due to over-sized particles. To overcome problems of the sort described, a novel, compact, drum-like fuel hopper fitted with the patented UKAF-NC (non-consolidating) feeder has been designed and built, and appears able to meter a variety of fuel materials. The NC-feeder-equipped hopper is unaffected by, and is usually able to feed, over-sized particles which tend to jam the mechanisms of other feeders. Fuel flowing from the feeder falls onto a flexible, centreless, screw conveyor which then carries it to the combustion appliance.

L'exploitation des systèmes de combustion fiables, efficaces, peu polluants, alimentés au bois sous forme de particules, exige un contrôle serré des vitesses d'écoulement de la masse du combustible et de l'air servant à la combustion. Jusqu'à présent, tous les petits systèmes commerciaux étaient équipés d'un mécanisme (habituellement une vis sans fin) qui à la fois mesure et achemine le combustible de la trémie de stockage vers le brûleur; ce système donne lieu à des irrégularités de l'alimentation qui se traduisent par une perte de maîtrise de la flamme soit à cause d'un tassement du combustible dans la trémie, habituellement à l'endroit où le combustible sort de la trémie, soit à cause d'un blocage dû à la présence de particules trop grosses. Pour résoudre ces difficultés, on a conçu et construit une trémie innovatrice, compacte, en forme de tambour, équipée du distributeur breveté UKAF-NC (non consolidant), qui semble pouvoir mesurer la quantité de divers types de matières combustibles. Le fonctionnement de la trémie équipée du distributeur NC n'est pas gêné par la présence de grosses particules, lesquelles ont tendance à bloquer les mécanismes des autres distributeurs. Le combustible qui s'écoule du distributeur tombe sur un transporteur à vis flexible, sans centre, qui l'achemine alors vers l'appareil de combustion.

INTRODUCTION

Experience with a number of small (under 60 kW output) automatically-fed, solid-fuel-fired central heating appliances has shown that all suffer from problems related to an inability to feed fuel reliably over long periods of time - over a heating season, for instance - from storage to the combustion chamber (1, 2, 3). Difficulties arise for several reasons; these include:

- lack of appreciation of the flow and other characteristics of the fuel by the equipment designers.
- use of conventional feeder mechanisms to remove material from the storage hopper; almost all of such mechanisms tend to compress, or in other words to consolidate, the fuel and thus to increase the fuel's resistance to flow.
- use of light weight components such as shafts and augers designed for use in agricultural applications but which are unable to withstand the forces imposed by consolidated wood particles and by over-sized particles. Such components become deformed or fail during operation.
- the relatively unrefined nature of the fuel results in over-sized particles occurring in the fuel; these either jam the feed mechanism, or alternatively, if they fail to flow from storage, they accumulate within the hopper over time to the extent that they partially or completely block flow of normal particles.
- abrasive mineral particles in the fuel which cause wear and lead to degradation of feeder performance.
- attempts by the owner-operator to use readily-available, low-cost fuels other than those

for which the appliance was designed by the manufacturer.

The non-consolidating bin feeder patented by UKAF Industries Inc. and developed for handling biomass in industrial applications by UKAF in conjunction with the British Columbia Research Corporation appeared to offer a way to over-come all the foregoing problems provided the mechanism could be arranged to fit and work in a small storage hopper. A compact, quiet, low-cost form of the feeder was required; this had to be capable of operating in such a manner that it did not adversely affect burner operation by admitting unwanted air, for example, and also had to be so arranged that dust or fungal spores in the fuel could not be discharged into living space. The thrust of the project described in this report was to develop such a feeder.

The specific requirements established to govern the design of the fuel feeder were as follows:

- must operate quietly to permit use in occupied space
- must be of such a size and weight, or be capable of being dismantled easily, so that it can be moved through residential doorways, hallways, around corners, and up or down steep basement stairs
- must be able to operate using standard 120 volt residential electrical supply
- should have a hopper capacity of at least 0.5cu m, and ideally of 1.0cu m
- should have an overall height no greater than 1200mm (48in) to facilitate manual re-filling
- must be able to handle a wide range of materials derived from both softwood and hardwood species and having moisture contents ranging from dry to 50% (wet basis) including the following:
  - fine sawdust (wood flour, sander dust)
  - coarse sawdust
  - small woodchips (12mm)
  - large woodchips (40mm)
  - pin chips (from small municipal drum-chippers)
  - planer shavings
  - hogged bark
- must be able to handle irregularly-shaped particles by feeding them from the storage hopper and, ideally, conveying them to the burner or moving them to a location where they can be readily removed
- must be able to handle over-sized (within reason) particles by feeding them from storage without stalling or damaging the machine, and moving them to a location where, if they are unable to enter the conveyor, they can be readily removed
- must be able to tolerate fine, abrasive material (sand, small stones) without damage to the feeder
- must be able to be serviced using commonly available household tools
- must be provided with access hatches to permit rapid and complete removal of any particles or other materials retained in the hopper, conveyor, or other parts of the system
- must use non-combustible, non-galvanized (or otherwise zinc-coated) materials in all components likely to be exposed to fire
- must be air-tight to prevent: (a) leakage of air into the combustion chamber through the fuel transport system, (b) reversed flow of gaseous products of combustion through the fuel transport system, (c) leakage of dust out of the system at any point, and (d) leakage of any fungal spores (that may be in the fuel) out of the system at any point
- should be driven by a single prime mover
- should be capable of being adjusted from one fuel type to another with the minimum number of modifications, and ideally by varying drive speed alone
- should be so designed and constructed that fuelling can be performed either manually or by mechanical means (conveyor)
- should incorporate both low-fuel-level and high-fuel-level sensors for alarm purposes and/or automatic control of the entire combustion system or of a refuelling conveyor
- should be capable of interconnecting with as large a range of combustion appliances (furnaces, boilers - both under-fired and over-fired) without requiring adjustment of the height of either appliance or the fuel feeder
- should be so arranged in terms of design, materials of construction, and fabrication that, if produced in quantity, the appliance could retail for about $1000.

DESIGN AND TESTING

Because of the numerous constraints imposed on the design, especially that of cost, time was spent considering and discussing a wide variety of ways of removing material of the type contemplated from the small hopper involved. Initially, thought was given to designs that would do the job without making use of the UKAF-NC feeder; the underlying reason for this approach lay in the intent to eliminate the bearings, rollers and other machine components required to support and guide the flexible belt material used in the NC feeder. Despite development of several interesting concepts, none of which used the UKAF-NC feeder, all were rejected because all in one way or another were perceived to have the high probability of feeding material from storage to the conveyor at a rate such as to over-supply the conveyor. If the conveyor intake port were to become flooded, then the conveyor would be required, in essence, to meter or regulate the flow of material. In other words, some of the time the material would flow out of storage and into the conveyor at an acceptable rate, and the conveyor would operate at, say, about 30% of capacity; at other times, when material

discharged from storage too rapidly, the conveyor would tend to run at close to 100% capacity and, furthermore, with its intake port flooded, it would be highly likely that the conveyor would jam. It became clear that whatever design was selected, it would have to employ a distinct separation of the feeding function (removal of material from storage), the metering function (control of the flow-rate of the material) and the conveying function. It was anticipated that metering control could be achieved within the feeding process if the UKAF-NC feeder were to be employed. The decision was taken, therefore, to proceed with design of a device incorporating the NC feeder.

Existing versions of the NC feeder involve applications of the feeder to large, industrial storage bins. In such installations, the feeder involves a slotted floor over which has been fitted an appropriate fabric that, in turn, is attached to the bin. The floor is arranged to move backwards and forwards inside the fabric and relative to the bin, while the fabric - attached to the bin - does not move, at least not relative to the material in the bin. In effect, the NC feeder provides a sliding floor with a discharge slot in it arranged in such a manner that the material lying on the floor is decoupled from the load-carrying structure of the floor. Due to the presence of the fabric covering, the material does not try to move with the floor as the floor slides; instead, it simply rests on the fabric. The only motion possible for any particle of the material is to fall through the slot when the slot appears under that particle. The design of the feeder is of a proprietary nature; information relative to it and to the specifics of its design and operation may be obtained from UKAF Industries (4) or B. C. Research (5). Because, in existing designs, the slot in the floor moves relative to the structure of the bin, this means that the place from which material flows from the bin moves continuously. This motion was considered to pose a problem in design of the small storage/feeder system because it would tend to cause material to be fed onto the conveyor, located beneath the feeder, in a non-uniform manner. The observation was made that, in this case, the storage hopper was very small, and that therefore, rather than cause the slot to move relative to the hopper, the slot would be held stationary and the hopper made to move relative to the slot. This arrangement would permit the slot to be held in position over the conveyor in-feed port, and would result in a uniform supply of material flowing onto the conveyor. A simple, inexpensive form of storage hopper was agreed upon and took the form of a circular drum of about 1. 2m (4ft) diameter and 0.6m (2ft) deep mounted with its axis orientated horizontally. The arrangement of the drum and feeder is such that the drum is rotated through about 90 degrees and then is reversed and rotated back to its starting position and the cycle repeated.

In order to test the design and to observe how material moved within the drum-shaped hopper and through the feeder, a full-scale transparent plastic model of the machine was built. The model was arranged so that most of its critical dimensions and settings could be altered quickly in order to permit rapid adjustments as neccessary. Initially, the model was unpowered because no estimate of the force required to operate it was available, nor was there any information relative to the speeds required. It was quickly observed that, regardless of the fuel type used, the drum could be turned relatively easily by hand; some rubbing friction was noticed due to the way the NC feeder belt was mounted outside the drum, and modifications were designed to eliminate this. More importantly, it was also noted that, provided the width of the slot was set to suit the test fuel being used, flow could be controlled very closely. When the drum was stopped, no fuel was discharged. When the drum was rotated, fuel flowed out of the slot, with the flow rate increasing as the rotational speed of the drum increased. Performance seemed so promising that a variable-speed electrical drive was arranged for the drum so that the machine's performance in terms of its ability to supply material at a constant flow-rate could be measured with the drum being operated at a pre-set, constant speed.

Initial tests, conducted using pulp-sized chips at 50% mcwb and with a feeder slot opening of 50mm (2in) indicated a high degree of control over particle flow rate, with no flow occurring when the feeder was stationary. Subsequent tests using dry hardwood sawdust indicated that the slot had to be reduced to about 7mm (1/4in) in order to achieve complete control of flow of this material; however, at this setting, a number of shavings and other particles were retained in the hopper. From these observations, it was concluded that either some way of quickly adjusting the feeder slot opening was required so that different fuels could be accommodated, or that a relatively large opening should be used for all fuels so that over-sized particles could be discharged, and that some other device should be added to control the rate of flow of the material; the decision was taken to pursue the latter option because it reduced the number of adjustments from fuel to fuel that would have to be made by the operator, especially in situations where new or unanticipated types of fuel were being used and the potential for selecting an inappropriate setting would be quite high.

In order to control flow rate, a small drum (of about 150mm (6in) diameter) and fitted with flexible helical flights was built and mounted under the feeder slot so that it rotated whenever the feeder drum moved. At the same time, additional spring-loaded idler rollers were installed to better guide the belt in order to eliminate the rubbing action of the belt referred to earlier; the spring mounting served both to maintain belt tension, and also to permit an automatic increase in slot width whenever a large particle - that otherwise could jam or damage the feeder - tried to pass through the feeder. The feeder slot was opened to about 130mm (5in), and the feeder system again tested with large pulp chips and with free-

flowing sawdust. The drum performed much as expected and made possible good control of flow with both materials, despite the wide slot setting. When tested with dry hardwood shavings, a material that other small feeders had been unable to handle due to its low bulk-density and poor flowability, the NC feeder system not only was able to feed all particles from the hopper, but also was able to control flow to within 10% when operating at a feed-rate of 18.4kg/h.

A crude but effective test of the machine's ability to cope with large over-sized particles was performed by placing a 300mm (12in) long piece of 40mm x 90mm (2in x 4in nominally) lumber in the hopper as the machine operated; the machine discharged this through the feeder and drum system without apparent difficulty.

Because the metering drum was friction driven through wheels bearing against the under-side of the hopper, it was caused to reverse direction whenever the hopper drive reversed; this caused some increase in loading of the entire drive system due to the effect of particles not yet discharged from the flights on the metering drum being carried back up against the mass of material in the space between the bottom of the slot and the metering drum. Because of this action, and because it was recognized that the metering drum either required flights or else had to be of very large diameter in order to control free-flowing materials, it was decided to replace the drum with an independently driven, flat conveyor belt mechanism. The belt could be made to run continuously in a single direction while the feeder supplied it with material. A variable-speed motor used to operate the belt conveyor would serve to regulate belt speed and therefore material flow-rate. The belt would discharge onto a screw conveyor which would be located to one side or the other of the fuel hopper (rather than directly beneath it, as had been the case with previous designs) thus reducing the overall height of the machine - in itself a desirable objective. Belt loading would take place by driving the feeder mechanism sufficiently quickly to ensure that the belt would be flooded, thus filling the space between the bottom of the feeder slot and the belt. It is a demonstrated characteristic of the NC feeder that it is unaffected by such flooding due to the action of the belting around the edges of the discharge slot, and therefore the strategy of flooding the belt was expected to pose no problems. A scraper mechanism, located above the belt and placed downstream of the point at which the belt is loaded, serves to scalp the material lying on the belt to ensure a uniform material depth on the belt. The drives for both the feeder system and for the flexible auger conveyor are taken from the same motor used to drive the metering belt system; a simple crank mechanism provides the reciprocating action required by the feeder, while a chain drive operates the auger. Use of a single motor ensures proper coordination of the speeds of the three major driven elements. The feeder reciprocates fast enough to ensure that the belt is flooded. The auger operates sufficiently faster than the metering belt to ensure that it runs at a small percentage of its capacity, thus reducing the power needed for it. In order to assess the performance of the preceding arrangement and to demonstrate its operation, a 1/4-scale model of the entire machine has been built. The model incorporates several design refinements not considered in the original machine - such as inclusion of a static top-loading port in order to facilitate re-filling. Preliminary test observations indicate that the mechanisms selected and the arrangement used work very well. It remains to construct a full-sized prototype and to test it with the range of available fuels.

The prototype, fabricated from drawings prepared for construction of the 1/4-scale model, will permit realistic estimation of the time and material costs to construct a fully operational machine. It is intended that the prototype embody features so as to meet all the specifications defined at the outset of this report; for example, the prototype will be fitted with a gasketted steel enclosure in order to make it both air and dust-tight. It is planned to install the prototype in a building and to operate it in conjunction with an appropriate warm-air furnace or hot-water boiler in order to monitor its performance in routine service.

CONCLUSIONS

The fuel feeding mechanism that has been developed is able to supply a wide variety of particulate-wood fuels at a controlled and easily adjusted rate. It is able to empty all particles from the hopper, and in doing so, is able to pass irregularly-shaped and over-sized pieces without becoming stalled or damaged.

ACKNOWLEDGEMENTS

Design concept formulation is due primarily to Mr. A. D. L. Skeath, UKAF Industries Inc. with much helpful advice also provided by Mr. Mark Skeath, also of UKAF and by Mr. N. Bundalli, B. C. Research Corporation. Much of the equipment fabrication and testing was performed by Mr. Mark Skeath. The author is deeply indebted to all these people for their unstinting help and support.

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P2-3
Central Tree Processing Plants
METHOD
RESULTS
CONCLUSIONS

IDENTIFICATION OF POTENTIAL PARTICIPANTS IN THE DEVELOPMENT OF A PROTOTYPE FULL TREE CENTRAL PROCESSING PLANT

Pierre Zundel and Rick Wightman

School of Forest Science, Université de Moncton

SUMMARY

A Canada-wide search for participants in the development of full tree centralprocessing was carried out. The potential of central processing to supply energy biomass is greatest in Atlantic Canada at current energy prices. Three forest industry companies in are participating in a feasibility study of the central processing concept in their operations. All three companies are in eastern Canada. Preliminary results of one transportation test are presented.

RESUME

On a recherché des compagnies intéressées à participer au développement d'une centrale de façonnage d'arbres entiers. C'est dans la région Atlantique que la centrale de façonnage d'arbre entiers sera la plus apte à fournir de la biomasse pour la production d'énergie à un prix rentable. Trois compagnies forestières de l'est canadien participent aux projet. Des résultats préliminaires d'une étude de transport d'arbres entiers sont présentés.

INTRODUCTION

Considerable efforts were expended during the last ten years developing forest harvesting systems which could recover hitherto unutilized material for the production of energy. One of the harvesting systems which was found to have the greatest potential was the full tree central processing system. This technology involves the harvest and trucking of trees with branches and tops still attached. Trees are then processed into standard logs and energy biomass at a central location. Designs were developed for the central processing plant (Hamilton, 1982) and feasibility studies were carried out (Lavoie, 1980; Routhier, 1981; Zundel, 1986). In 1986 a proposal was presented by the author which led to the award of a contract in 1988 to identify and rank potential participants in the construction of a full-tree central processing plant. This paper summarizes the mid-project results of the research in this area.

METHOD

In order to assess where the central processing technology is most likely to be attractive, it is necessary to understand the fundamental characteristics of the process. The following factors should therefore noted:

1) The transportation of full trees will only be possible where trees are sufficiently small to be loaded in their entirety on a truck trailer.

2) The lower bulk density of the full trees will increase the cost of truck transportation unless hauling is done on a road network where trailer dimensions may be increased beyond legal highway size limits to compensate.

3) Leaving processing functions such as delimbing, slashing and residue chipping to a central plant rather than carrying them out in the woods will improve the efficiency of these operations.

4) By increasing the amount of processing done at a plant, the number of people to be housed in the woods is reduced, which results in lower logging camp costs.

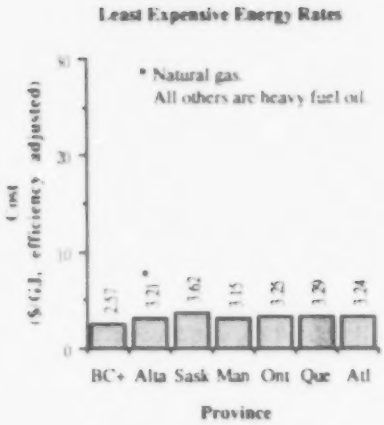

Figure 1. Least expensive energy rates by region.

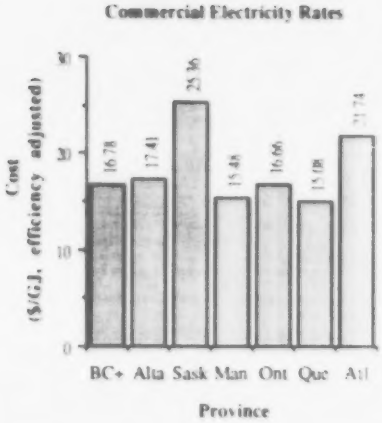

Figure 2. Electrical rates by region.

5) The transportation of branches and tops to a mill reduces the amount of slash left in the stump area or at roadside, which may reduce reforestation and slash disposal costs (and may, in some cases, cause soil nutrient depletion).

These considerations indicate that central processing of full trees will be most attractive in areas east of British Columbia's Coastal range, in off-highway hauls. The benefits of this system will be greatest where logging camp costs are high and where slash disposal poses a problem.

It is clear that the value of the biomass generated as an energy source is the major factor affecting the financial attractiveness of central processing. In order to assess this factor, it is necessary to understand the cost of energy sources other than biomass.

RESULTS

Figure 1 shows the cheapest source of energy for each region and its cost (adjusted for different efficiencies in use). These costs reflect the estimates of Energy Mines and Resources Canada (1989) for commercial use of heavy fuel oil, electricity and natural gas by region.

It is clear from Figure 1 that petroleum products (usualy heavy fuel oil) are currently the cheapest sources of energy. Figure 2 shows the electrical rates across Canada. It is clear from this that Saskatchewan and the Atlantic region have the highest electrical costs. In addition to this, certain regions of Canada, particularly in the North, may not be serviced by the provincial electrical grid and thus be subject to much higher costs than are reflected in the regional averages shown (Ontario Hydro, 1982). It is also important to note that natural gas is available in limited quantities in the Atlantic Region (Shushmagera, 1989).

In addition to this, the amount of biomass from alternate sources will also have an effect. Where large amounts of mill residues are available, it is unlikely that biomass from harvesting residues will be competitive. Areas such as British Columbia have large quantities of these residues which are currently available. In the Atlantic region, a greater portion of the mill residues are already utilised. In New Brunswick, for example, over 80 % of the mill residues are already being used.

In order to assess the interest in the forest industry individual companies and industry associations were visited over the course of twelve months. A wide ranging mail and telephone survey was also carried out with the object of identifying three participants for whom detailed transportation trials and feasibility studies might be undertaken.

The results of the mail and telephone survey corroborate the theories regarding the potential interest. As a result of these efforts, three participants were identified:

1) Fraser Inc. (Plaster Rock, NB)
2) J.D. Irving (St. Leonard, NB)
3) La Societe Kruger Inc. (Montreal, QC)

The first two participants are integrated pulp and sawmilling companies with extensive private holdings in New Brunswick. In both cases the operations for which central processing is being considered involve off-highway hauls with oversized truck trailers. A market (local and export) exists for biomass and wood-based electricity production is expected to increase in the region.

The third is primarily a pulp and paper manufacturer with interests in sawmills as chip sources. Their interest comes from the possibility of combining a sawmill, pulp chip facility and biomass production. Off-highway hauls are also a possibility in this case.

It should be noted that several operations in Western Canada were using full tree hauling (with no recovery of branches for energy) and central processing (Harrison, 1988; Konkin, 1989). The availability of alternate sources of biomass, of cheap natural gas and of low cost electricity were cited as reasons for not considering central processing in most of the West. Considerable interest was also demonstrated in PEI (McKnight, 1988) and Nova Scotia (Stockman, 1988).

A winter transportation study was carried out at the Fraser operation in Plaster Rock, New Brunswick, in December 1988. The results indicated that the expected reduction in bulk density occured. Full tree loads averaged 54 green tonnes while tree-length loads averaged 60 green tonnes. The full tree loads were made up of 11% biomass and 89% of conventional products. This represents a 20 % reduction in the size of the load of conventional products carried as tree lengths. This is a slight underestimate of the actual load size achievable with the trailers used since loads were built smaller in order for trucks to clear high-voltage distribution wires near the mill.
It will, however be possible to compensate this with larger trailers. The trailers used in the study area are already much larger than standard highway trailers. The largest trucks used in this study measured 5.2m (height) by 4.3m (width) versus 4.0m by 2.44m for standard highway trucks.

Transportation trials will be carried out in summer conditions on the operations of all three participants when roads become operable in May and June, 1989.

CONCLUSIONS

Conclusions on the financial feasibility of the central processing concept in the operations of the participating companies will have to await the final hauling trials and the detailed financial analysis. It is clear however that considerable interest in this technology exists.

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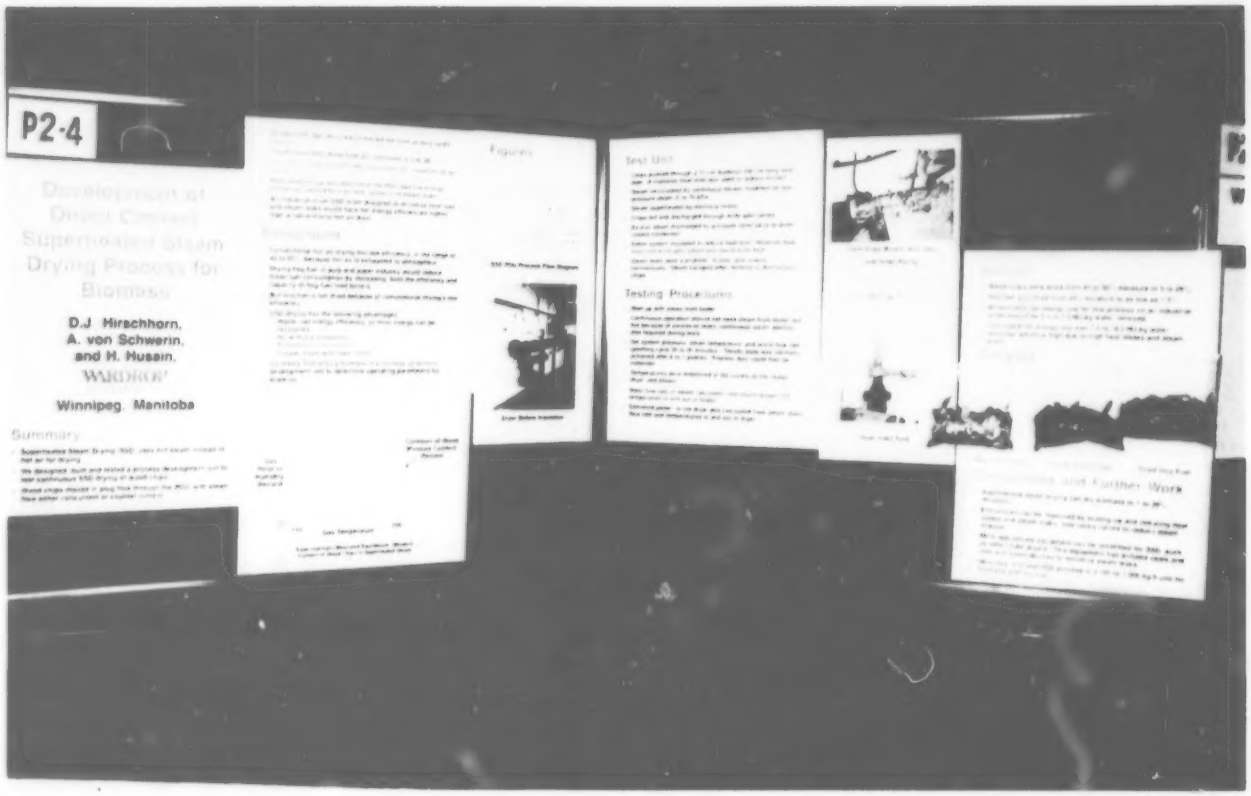
P2-4
Development of Direct Contact Superheated Steam Drying Process for Biomass
D.J. Hirschhorn, A. von Schwerin, and H. Husain.
WARDROP
Winnipeg, Manitoba
Summary
Figures
Test Unit
Testing Procedures

DEVELOPMENT OF DIRECT CONTACT SUPERHEATED STEAM DRYING PROCESS FOR BIOMASS

D.J. Hirschhorn, A. von Schwerin, and H. Husain

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Superheated steam drying (SSD) employs steam instead of hot air to more efficiently dry a product. Wardrop designed and built a process development unit to test the SSD technique for drying wood chips and hog fuel under continuous, plug flow conditions at steady state. The experimental data was used to calculate energy balances and to estimate transfer coefficients. These will be used to prepare conceptual design and cost estimates of an industrial scale unit for comparison with conventional hot air drying.

Le séchage à la vapeur surchauffée (SVS) consiste à utiliser de la vapeur au lieu d'air chaud pour séher un produit. Wardrop a conçu et construit une unité de mise au point du procédé pour évaluer le séchage de copeaux de bois et déchets de bois écrasé par SVS sous des conditions constante. Les données expérimentales ont été utilisées pour calculer les bilans énergétiques et pour estimer les coefficients thermiques et les coefficients de transf..t de masse. Ces valeurs vont ensuite être utilisées pour élaborer le plan d'un séchoir à vapeur surchauffée d'échelle industrielle et en valeur le coût, en vue de comparer cette méthode avec la méthode de séchage à air chaud.

INTRODUCTION

Drying with hot air is a common unit operation in industry that uses a significant amount of energy. Efficiencies are often in the range of 40-60 percent because the hot dryer exhaust, containing both remaining sensible heat plus the latent heat of the water evaporated, is discharged to the atmosphere.

The Superheated Steam Drying (SSD) process uses superheated steam for delivering the energy for dehydration instead of hot air.

Figure 1 shows the concept of SSD drying. Superheated steam heats the wet feed and evaporates most of the water from it, producing a dry product. The gas exiting the dryer is essentially all steam, made up of the inlet steam plus the water that evaporated from the feed. Most of the outlet steam can be recycled to the dryer after superheating, while the excess steam can be used for other heating uses, recovering most of the energy input to the SSD system. Surface heat losses and steam leaks reduce heat recovery rates.

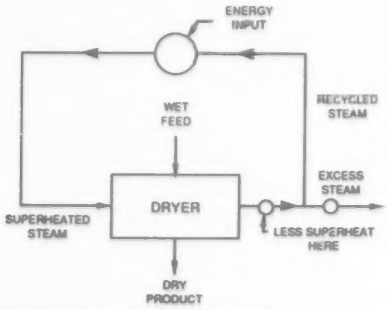

Figure 1. Superheated Steam Drying Concept

Besides lower net energy consumption, SSD drying has several potential benefits over conventional hot air drying:

- No airborne emissions.
- Prevention of dryer fires.
- Product not exposed to hot oxygen or combustion products.
- Smaller dryer with lower costs.

The goal of this project is to test the SSD process for biomass at the pilot scale, and based on test results to assess its economics at an industrial scale for comparison with conventional hot air drying. Wood chips were used for most tests as a representative biomass because our dryer was built for handling chips. However, one test was performed to demonstrate that drying of hog fuel is technically feasible with the SSD Process.

BACKGROUND

References on drying in superheated vapours in the literature go as far back as 1908 (1). Spray, fluid bed, and flash dryers have been built for SSD drying (2-10). Many products have been dried in superheated steam, including lumber, hog fuel, peat, beet pulp, orange peel, etc. A pilot scale SSD lumber dryer was shown to produce good quality lumber in much shorter times than a conventional lumber kiln (3). An SSD spray dryer was used to dry clay slip (11).

Scandanavia seems to lead the world in SSD industrial scale applications. MoDo-Chemetics, a Swedish firm, sells an SSD flash dryer system that has been used to dry peat at industrial scale (4,5). DDS uses an SSD fluid bed dryer to dry beet pulp in one of their plants in Denmark (7). In Finland, research is underway on drying peat with a pilot scale fluid bed SSD dryer (2). There has been some work in Canada on SSD

drying, and a patent was issued on a SSD spray dryer (10) in 1972. Work on powering an SSD spray dryer with a water plasma torch at temperatures over 6000K was done at McGill University (8,9), and a batch bench scale SSD hog fuel dryer has been tested (6).

Several previous designs propose using vapour recompression to power an SSD dryer, that is taking the excess low pressure steam generated by the dryer and compressing it to a pressure sufficiently high to be able to use it as the heat source for the dryer (6,11).

Our goal was to test a continuous biomass SSD dryer, and to be able to use the results to retrofit conventional hot air drying equipment for SSD drying. While rotary kiln driers were initially envisioned as our target market, it now appears that using steam tube dryers with the outside vessel stationary would be more appropriate, as this equipment would be easier to seal.

SSD PROCESS DEVELOPMENT UNIT

Wardrop designed and built a continuous process development unit (PDU) to test SSD drying of wood chips. Figure 2 shows a process flow diagram for the PDU. Chips are pushed as a plug through the dryer by a piston driven by a pneumatic cylinder. Superheated steam can be introduced both cocurrent and countercurrent to wood flow, although the former is the preferred mode of operation to prevent overheating of the product. A blower, modified for use with steam at low pressures (0-70 kPa), is used to recycle the dryer exhaust to an electric heater that superheated the steam. Excess steam is vented by a pressure relief valve to a condenser. Steam from a gas-fired boiler (55-100 kPa) is used for start-up.

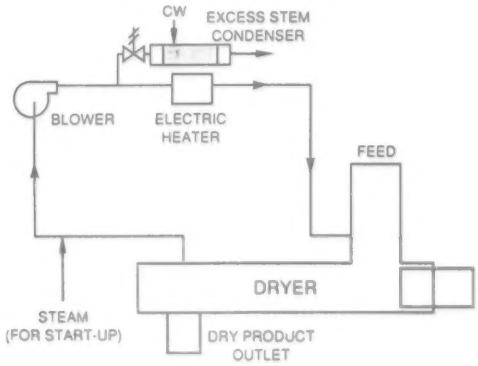

Figure 2. SSD PDU Process Flow Diagram

RESULTS

Several tests were performed drying wood chips at several different operating conditions. System pressure, steam temperature to the dryer, and wood chip feeding rate were varied, for both cocurrent and countercurrent operation. Steady state operation was achieved for runs lasting as long as 69 hours. A wide range of conditions were tested, as can be seen from the product moisture content which ranged from over 40 percent to less than 1 percent. (Feed chips were 45-50 percent.)

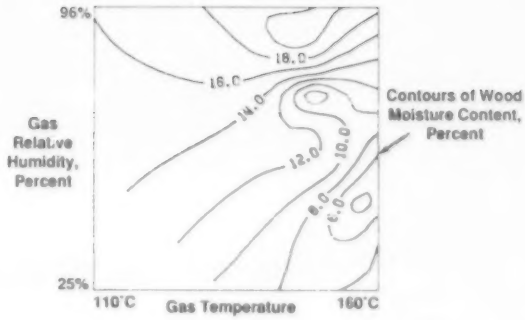

Figure 3. Experimentally Measured Equilibrium Moisture Content of Wood Chips in Superheated Steam

Figure 3 presents a contour plot of product moisture content for different dryer outlet temperatures and relative humidities. The dryest product is produced at high gas temperatures and low relative humditities. Relative humidity for superheated steam is calculated from temperature and pressure and is equal to the absolute pressure devided by the saturation pressure of water at that temperature:

$$R.H. = \frac{P}{Psat\ (T)}$$

Mass and energy balances were prepared for each steady state condition. The mass flow rate of steam into the dryer was calculated from steam temperatures in and out of the heater and the heater power draw. Power delivered to the dryer was estimated from steam temperatures in and out of it, and the steam mass flow rate. The power used for drying was calculated from the rate of drying, permitting the calculation of dryer efficiency.

The PDU dryer efficiency was much lower than expected, in the range of 10-35 percent. Energy consumption was in the range of 7.5 to 18 MJ/kg of water removed, even when crediting for possible energy recovery. This was caused primarily by high heat loss rates from the dryer, and secondly by significant steam leakage. While the straight sides of the 20 cm pipe making up the dryer were well insulated, we estimate that heat loss from the knife gate valves was high enough to account for these low efficiencies. Steam leaks, mostly from the pusher shaft seal, and steam losses when feeding and removing chips, would also reduce efficiency. These steam leaks were large enough to prevent operation at 55 kPa without the boiler steam valve being open a bit at all times. Also, because of these leaks, no condensate was collected from the excess steam condenser except when the boiler steam valve was open, which made checking the mass balance impossible.

During one run, we tested the drying of hog fuel obtained from a pulp mill (Abitibi Price, Pine Falls, Manitoba). We continued feeding it at the same rate as the chips, but since the hog fuel was 65-69 percent moisture, this feeding rate was too fast and the dryer plugged up. Wet biomass was much more difficult to push through the dryer than dry biomass, and if the

feed is introduced too quickly, the entire bed becomes too wet. Normal operation allowed for adequate drying before pushing to achieve steady movement of material through the dryer. After shutting down and removing some of the dryer contents manually, and starting up feeding at a slower rate, the system did manage to dry the hog fuel remaining in the dryer. The product moisture content dropped from 48 percent to 1.3 percent over the next 4 hours, until wood chips came out as product.

The hog fuel was also very stringy which would require different solids handling techniques than chips. Feeding hog fuel through a 10cm diameter pipe was extremely difficult, while feeding chips was easy. And the stringiness would probably preclude using paddle or ribbon conveyors with hog fuel.

DISCUSSION

Our success in drying wood chips and hog fuel indicate that SSD drying would be useful for industrial applications. The low efficiencies encountered should not be a concern because we estimate that with a proper design the system efficiency should be much higher at an industrial scale due to proportionally less heat loss. In theory, with no heat loss, the efficiency should be infinite because all input energy should be recovered. However, since heat loss from a conventional dryer are in the order of 5 percent and allowing for some energy not being recovered, we expect only 60-80 percent energy recovery resulting in efficiencies of 250 to 500 percent and net energy consumption of 0.5-1.0 MJ/kg of water removed. These efficiency calculations use 2.25 MJ/kg of water evaporated as the basis.

Industrial scale SSD drying of biomass would require a mechanical design different than the PDU. Instead of pushing, either paddles of various sizes, shapes, and angles, or a ribbon conveyor, or a screw conveyor would be used to convey the biomass through a dryer, depending on the nature of the biomass. Different valve designs, with low steam leaks, should be considered for feeding and discharging the product. An industrial scale system could use high pressure steam or a gas fired heater to superheat the steam instead of electricity.

POTENTIAL APPLICATIONS

The key application is the drying of hog fuel by the pulp and paper industry. The process could, while consuming only 20 percent of the energy required by the conventional drying process, increase the hog fuel combustion efficiency by up to 25 percent and increase the firing rate of hog fuel boilers as well (13,14). Resulting reduction in fossil fuel used by the pulp and paper industry would be extremely large if this application is commercialized.

According to a study by Pulp and Paper Research Institute of Canada, 11 Western Canadian Kraft mills used an average of 5.9 GJ equivalent of hog fuel per tonne of pulp produced, and 6 Eastern mills 2.1 GJ/t. Each of these mills purchased fossil fuels. Improvements in the combustion efficiency of hog fuel would result in major reductions in the total fossil fuel use by the Canadian pulp and paper industry.

Other drying applications that should be tested include:

- Wood chips for chip-board;
- Biomass before hydrolysis pretreatment;
- Distiller's dried grain (DDG);
- Food products (examples are potato granules, starch, coffee, dairy products);
- Systems with organic solvents.

For several of these applications, SSD drying might produce a product with different properties. This might pose a problem, but might be an advantage. For example, CPC has a patent on a high product temperature flash dryer for drying starch that operates as an SSD dryer (12). The moist starch feed is gelatinited before drying takes place, resulting in a product that is dustless and granular with the consistency of fine sand. Each application requires testing.

CONCLUSIONS

Our tests show that Superheated Steam Drying (SSD) is an effective method for drying biomass and has significant potential for being economical at an industrial scale. Other advantages for SSD drying include no airborne emissions, the prevention of dryer fires, not exposing the product to hot oxygen or combustion products, and a smaller dryer with lower costs. An attractive application for SSD is drying hog fuel at pulp mills, which if developed would reduce the fossil fuel consumption of the pulp and paper industry. Many other applications are also possible.

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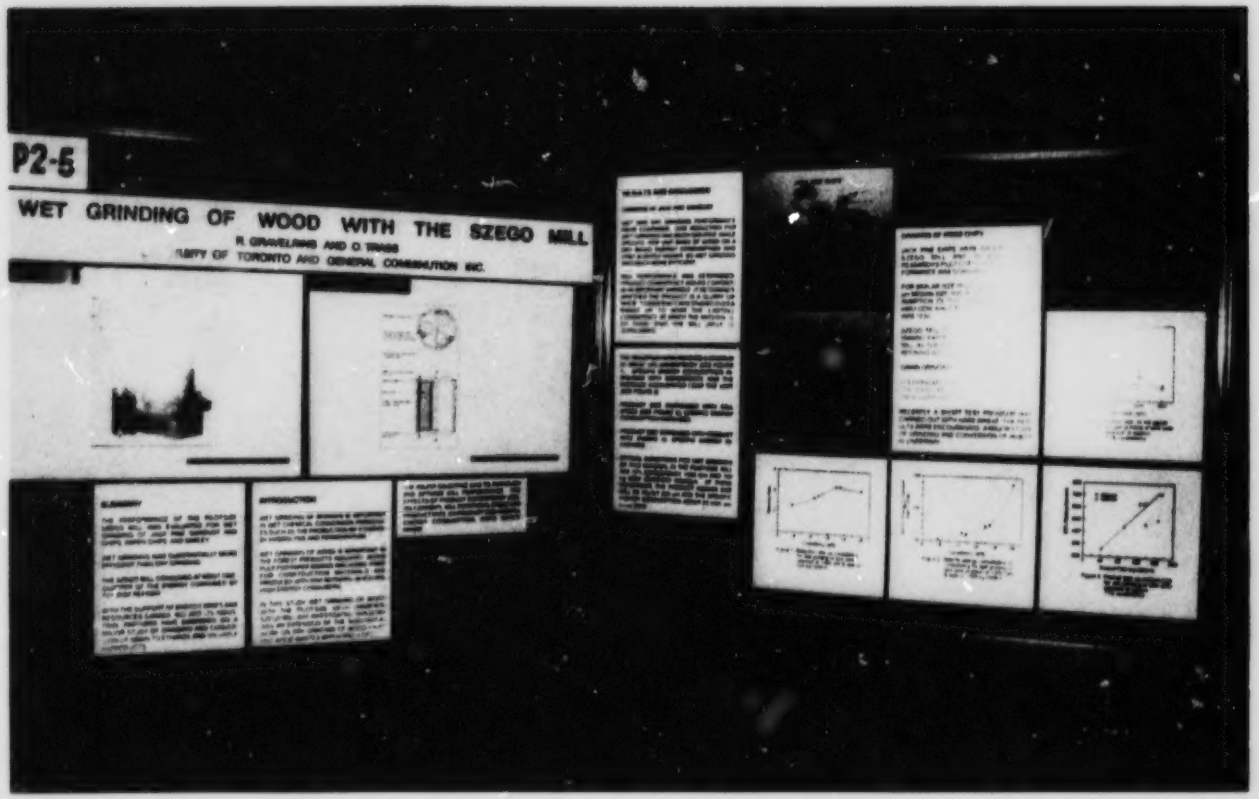
P2-5
WET GRINDING OF WOOD WITH THE SZEGO MILL
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WET GRINDING OF WOOD WITH THE SZEGO MILL

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Jackpine sawdust and chips, and aspen chips were ground wet in the pilot-size Szego Mill. Fine grinding for bioconversion was investigated, and mill performance was compared to that of the disk refiner. At the appropriate conditions, the product median size after one pass through the mill was less than 150 µm. The specific energy consumption (energy per unit mass of wood on a dry basis) is at most one-quarter that of the disk refiner. Use of the energy-efficient Szego Mill as the first stage in multi-stage refining to produce mechanical pulp, and to produce wood fibre for construction materials, will be examined.

Du bran de scie et des copeaux de pin gris, ainsi que des copeaux de tremble ont été broyés à l'état humide dans un broyeur pilote Szego. On a étudié la finesse de broyage en vue de la bioconversion, et on a comparé le rendement du broyeur à celui du raffineur à disques. Dans les conditions appropriées, la granulométrie médiane du produit après un passage dans le broyeur était inférieure à 150 µm. La consommation spécifique d'énergie (énergie par unité de masse de bois sec) est d'au plus un quartième de celle du raffineur à disques. On examinera l'utilisation du broyeur Szego (qui consomme peu d'énergie), en tant que première étape du raffinage qui en compte plusieurs, en vue de produire de la pâte mécanique et des fibres de bois destinées à la fabrication de matériaux de construction.

INTRODUCTION

Wet grinding of wood is important in a number of applications, notably, wet chemical conversion processes such as the conversion of wood waste to ethanol by hydrolysis and fermentation, and wood liquefaction. Comminution increases surface area and, in the case of lignocellulosic materials such as wood, disrupts the lignocellulosic matrix and the cellulose itself. Both the surface area increase and the disruption result in much higher bioconversion reaction rates and increased yields (Millet et al, 1979).

Important applications of wet grinding of wood are also found in the forest products industry. Wood pulp for paper making, and wood fibre for construction materials, such as composite boards and molded products, are produced extensively by comminution in disk refiners. However, disk refiners are high energy consumers, requiring about 400 kWh/t ODW (tonne of wood on an oven-dry basis) to make construction materials, and 1900 kWh/t ODW to make printing materials (Franzen, 1984).

In this paper, the results of a study of wet grinding of wood with the Szego Mill are described briefly. This study was an extension of the substantial work on dry grinding of wood chips and wood wastes which preceded it. The latter was presented at the Sixth Bioenergy R & D Seminar in Vancouver in 1987.

The major objective of the present study was to establish and optimize the performance of the pilot-size (22-cm diameter) Szego Mill for wet grinding of wood. The effects of various feed and operating variables were investigated. The feed variables included the type of material and its moisture content. The operating variables included the mill rotational speed, the rate of material through the mill, and the rate at which water is added to the mill. (The rate of material on a dry basis, its moisture content and the water rate determine the mill product solids content or consistency.) The effects of these variables on mill capacity, product particle characteristics, especially size, and mill power consumption, were studied.

The tests were done with the pilot unit, consisting of a feeding system, the mill, and a product receiver, at General Comminution Inc. (GCI)'s laboratory at the University of Toronto. The pilot mill is 22 cm in diameter and contains three 30-cm long, helically-grooved rollers (see Figure 1). The rollers are radially mobile: they are attached to the rotor by rigid shafts whose diameter is narrower than the roller inside diameter. The roller assembly is driven by a 15 or 20-hp electric motor. Material falls onto the top driving plate of the rotor and is thrown to the sides of the mill by centrifugal force. Water is added at this point. The material then passes down the mill between the stationary grinding shell and the rollers, which rotate in a direction opposite to that of the rotor due to friction and centrifugal force.

Material is ground by a combination of crushing and shearing forces exerted by the rollers, which run over it repeatedly. The helical roller grooves help transport material down the mill. Two types of rollers, standard and wide-grooved, were used. Using wide grooves avoids the clogging problems which may occur with some materials. Wet-ground product exits through an outlet at the bottom of the mill and falls into a receiver.

Run length was typically three minutes. Mill rotational speed was measured with a tachometer. The product rate was measured by weighing the amount collected at the mill exit over a timed interval. Feed moisture content and product consistency (solids content) were determined by weighing samples, placing them in an oven at approximately 104 °C, and weighing them again when they were oven-dry. The measured value of product rate and consistency were used to calculate the rate of wood on a dry basis. Particle-size distribution was determined using a method developed for wet-ground wood products, using the custom-built wet-sieving device at GCI's laboratory. For the pilot mill equipped with an electronic inverter, the power consumed by the mill drive was measured by a power meter and logged by a microcomputer. For the other pilot mill, power consumption was calculated from the time-averaged current, obtained from digital ammeter readings, and the motor manufacturer's performance data.

RESULTS AND DISCUSSION

Grinding of Jack Pine Sawdust

The essential objective in grinding this material was to establish the performance of the mill over a range of operating conditions, as was done for dry grinding of woody materials (Gravelsins and Trass, 1986). Conversion to ethanol by hydrolysis and fermentation was also considered. The most stringent specification for this application was that essentially all the product could pass through a sieve with apertures of 850 µm.

The effects of product consistency, mill rotational speed and oven-dry rate of material on product particle-size distribution and mill power consumption were determined rather thoroughly. Consistency was varied from 6 to 16%; mill speed from 600 to 1200 rpm; and product rate from about 40 to 170 kg ODW/h. The sawdust was moist or "green", containing about 40 wt% moisture when received. A slight improvement in performance was observed when the moist feed was soaked before grinding. Subsequently, all wet grinding tests were done with soaked feed. The standard rollers were used for all of these tests because these rollers have more grinding surface per unit length than wide-grooved rollers, and groove clogging does not occur with sawdust. The results of these tests were first reported by Meffe (1988).

Initially, in order to compare the two methods of grinding, a pair of runs were made at virtually identical conditions except than in one case moist sawdust was ground wet, and in the other, air-dry sawdust was ground dry. The specific energy consumption (power consumption divided by the product rate on an oven-dry basis) of the wet-grinding run was somewhat higher than that of the dry-grinding run, but the degree of size reduction for wet grinding was much greater than that for dry grinding. Clearly, the efficiency of wet grinding was far superior to that of dry grinding. In the case of moist feed, another advantage of wet grinding is that the formation of relatively large agglomerates is avoided. Agglomerate formation limits the degree of size reduction that can be achieved when moist woody materials are dry-ground (Gravelsins and Trass, 1986).

Product consistency is a very important variable. It determines the nature of the product, i.e., whether it is a slurry or a paste, and strongly affects mill performance. For each material, there is an upper operating limit for consistency. At the limiting consistency, mill plugging is approached and power consumption is very high. The limiting product consistency for wet grinding of jack pine sawdust in the pilot mill was found to be approximately 17% (it is expected that this limit would be somewhat higher if an open-bottom Szego Mill were used). Mill performance was then determined over a range of consistency up to near the limit.

Reduction ratio (characteristic feed size divided by the corresponding product size) and specific energy consumption were correlated with product consistency (refer to Figures 2 and 3, respectively). Size reduction decreased at consistencies below the region near the limiting consistency. There was a peak in the degree of size reduction at approximately 12.5 to 14.5% consistency. A decrease in performance occurred at high consistencies approaching that of mill plugging. Specific energy consumption increased with consistency, and the increase accelerated above 12.5%. The accelerated increase in specific energy consumption appears to coincide with the decrease in size reduction.

The effect of mill speed on product size, represented by the 80%-passing size, is shown in Figure 4. Product size decreased as mill speed was increased. Specific energy consumption increased with mill speed. (Because of space limitations, the plot of specific energy vs mill speed is not included here.) The trends for product size and specific energy consumption were similar to those for dry grinding (Gravelsins and Trass, 1986).

The maximum desirable mill speed for the 22-cm mill for prolonged operation, depending on the type of feed material, is about 1000 rpm. Above the maximum desirable speed, wear of mill components increases significantly.

Figure 5 illustrates the dependence of product size on product rate, on an oven-dry basis. Product size increased as the product rate was increased. Specific energy consumption (not shown) decreased with product rate. Again the trends were similar to those for dry grinding.

Optimum conditions for wet grinding of jack pine sawdust in the 22-cm Szego Mill were considered. Single-pass grinding with soaked feed was presumed. Two approaches to selecting optimum conditions were used. In the first approach, the size specification for hydrolysis, that essentially all product be able to pass an 850-µm sieve, was chosen as the primary criterion.

For product consistency, the best results were at about 13%. When the mill was operated so that the product was thicker or thinner, the product was coarser. Mill speed is a crucial variable. There was a drastic decrease in performance at speeds significantly below 1000 rpm. This is consistent with results for dry grinding of wood in the Szego Mill, where there is a relatively high critical speed (or narrow range of speeds) below which comminution of wood, a tough material, is ineffective. Regarding product rate, it is possible to make product such that virtually nothing is retained on an 850-µm sieve by operating at a sufficiently low rate, e.g., at 40 kg ODW/h in the pilot mill. If 97% passing 850 µm is acceptable, then one can run the pilot mill at about 110 kg ODW/h with a speed of 1000 rpm and a product consistency of about 11%.

A second approach to determining optimum grinding conditions, when the product size specification is not crucial, is to consider grinding efficiency as expressed by parameters such as the Bond Work Index. The Bond index is specific energy consumption divided by a parameter representing the degree of size reduction. It is thus an inverse measure of grinding efficiency: the higher the index, the lower the grinding efficiency.

The Bond Work Index was plotted against consistency, mill speed and product rate. The index did not vary with consistency until near the maximum operable consistency, where there was a steep increase. Thus one would choose a high consistency, say 13%, which is still below the region of steep increase. The plot of work index vs mill speed gave little indication of the optimum speed, so mill speed would be chosen on another basis. The plot of work index vs product rate did suggest optimal rates. The index descended to a plateau at about 100 kg ODW/h, therefore one would operate at a rate exceeding this.

Grinding of Wood Chips

Jack pine chips were obtained from Abitibi-Price's Research Centre in Mississauga, Ontario. Abitibi-Price were conducting tests with the chips on a pilot-size disk refiner. Our major objective was to compare the performance of the Szego Mill, in terms of size reduction, power consumption, and suitability for applications such as paper-making, to that of the disk refiner.

The performance of the two mills is compared in Table 1. Both products described are first-pass products. The Szego Mill pulp was obtained by wet screening the mill product to remove a fraction of very coarse material which had bypassed the rollers, and then dewatering the slurry with a fine screen.

It should be noted that the mills operate at significantly different temperatures. Because of the large input of mechanical energy to a confined space, the temperature in a refiner exceeds the boiling point of water. Steam exits along with product at the refiner outlet. In wet grinding with the Szego Mill, the product temperature

is essentially that of the water added to the mill. The strengths of the wood components, cellulose, hemicellulose and lignin, decrease with temperature. This reduces the energy required to break the chips down, and also affects how the chips fracture (Back and Salmen, 1982). Running the Szego Mill at higher temperatures should be investigated.

The specific energy consumption for the Szego Mill pulp product was about one-quarter that of the disk refiner product despite that this particular Szego Mill run was relatively inefficient, because the rate had been set very low to produce a fine and pulpy product. From the GCI wet-sieving analysis, the Szego Mill pulp and disk refiner pulp were about the same size. Size classification was also done by Abitibi-Price with a 'Bauer-McNett' device, which is used by the pulp and paper industry to analyse fibre length in pulps (Clark, 1985). Those results indicated that the Szego Mill pulp was finer than disk refiner pulp.

Microscopic analysis has revealed that the particles in the two pulps are of a fundamentally different nature. Most of the Szego Mill pulp particles are flattened fibre (wood cell) bundles with aspect (length-to-width) ratios of the order of 5. Most of the disk refiner pulp particles are much narrower and somewhat longer, with aspect ratios of the order of 10 to 20. They are flexible, whereas the Szego Mill product particles are stiff.

Abitibi-Price found that the Szego Mill pulp was unsuitable for paper making. It was not possible to form hand sheets, which are used to test paper strength and other properties, from the pulp. The pulp particles did not bind to each other properly. Although disappointing, this is not surprising when the comminution actions of the mills are considered. In the Szego Mill, at the operating conditions used, randomly-oriented particles are crushed between the roller ridge and the wall. Particles at the edges of the ridge are bent and broken. In the disk refiner, the wood fibres are sheared apart and, to some extent, fibrillated (unravelled) by radial bars. The wood fibres orient perpendicular to the bars, and fibre length is largely preserved (Franzen, 1984).

It may still be feasible to employ the Szego Mill in paper making, taking advantage of its significantly lower energy consumption. Rather than grinding chips in the Szego Mill at severe conditions to maximize size reduction and thus producing an unsuitable pulp, the mill might be used in a first stage at moderate grinding conditions, with disk refiners being used in the subsequent stage(s). Disk refining is often done in multiple stages (Franzen, 1984). Szego milling parameters which should be investigated, in addition to consistency, mill speed, and product rate, are steaming of the chips before grinding, and grinding at high temperature in general, and use of alternate roller designs to shear the fibres apart without reducing their length.

Use of the mill in place of a disk refiner should also be investigated for manufacturing wood fibre for construction materials. Wood fibre for such applications is considerably coarser than wood pulp for paper making (Franzen, 1984), and no doubt fibre quality is of far less concern. Again the benefit of the Szego Mill would be its substantially lower energy consumption. Dry grinding of moist chips (Gravelsins and Trass, 1986) may be more suitable for such applications.

Mill performance was also evaluated for wet grinding of aspen chips. Because of space limitations, the results are not included here. The interested reader is referred to the full report (Gravelsins and Trass, 1989).

GRAIN GRINDING

A modest amount of work with grain was done in Phase I of the study, "Grinding of Wood Chips, Bark and Grain to Fine Powders", for Energy, Mines, and Resources Canada (Gravelsins and Trass, 1986). During this phase it was agreed to extend the work to include fermentation trials, which were conducted by Professor Wayman at the University of Toronto. The results were encouraging in that significant improvements in yield of ethanol from barley, compared to conventional processing, were achieved by wet grinding of steeped barley in the Szego Mill.

During the summer of 1988, a short test program was carried out with hard wheat. The results were as encouraging as with barley. With the support of Energy, Mines and Resources Canada, GCI and its industrial partners have embarked on a major study in this area.

SUMMARY AND CONCLUSIONS

1. The performance of the pilot-size Szego Mill was evaluated for wet grinding of jack pine sawdust and chips, and aspen chips. The effects of product consistency, mill rotational speed and product rate, on product size and mill energy consumption, were evaluated. Optimal conditions were determined with respect to a size specification for hydrolysis, and grinding efficiency as measured by the Bond Work Index.

2. In terms of energy expenditure for a given degree of size reduction, wet grinding is substantially more efficient than dry grinding.

3. The Szego Mill requires one-quarter or less the energy that the disk refiner does. Szego Mill product is not suitable for making paper directly, but use of the mill as the first stage in a mechanical refining sequence will be investigated.

4. With the support of Energy, Mines and Resources Canada, GCI and its industrial partners have embarked on a major study of grinding and conversion of grain and other types of biomass to ethanol and valuable byproducts.

ACKNOWLEDGEMENTS

The test work was supported financially by Energy, Mines and Resources Canada. S. Meffe carried out the sawdust grinding work under the supervision of R. Gravelsins. I. Fujs helped carry out the wood chip grinding experiments. Abitibi-Price Research contributed generously by carrying out analyses, making their test data available, and providing feed material. The E.B. Eddy Nairn, Ontario Sawmill kindly provided a large amount of feed material.

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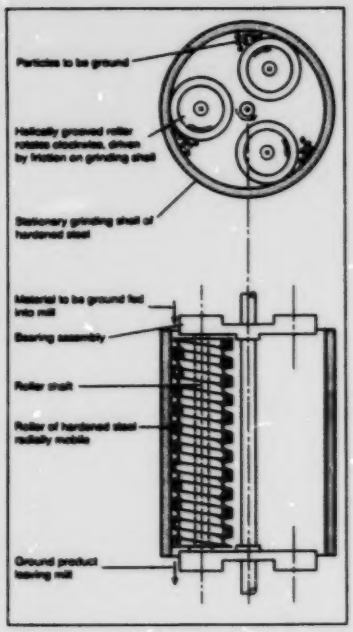


Figure 1 Schematic diagram of the Szego Mill

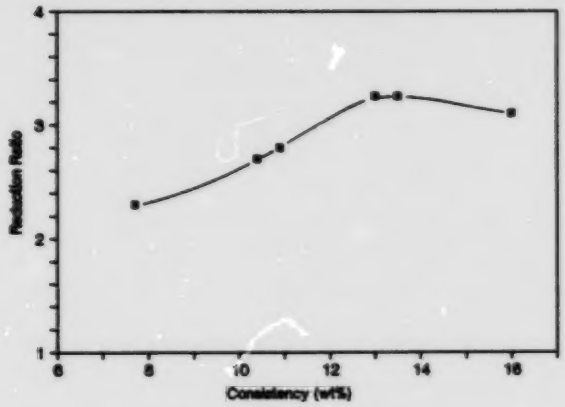


Figure 2 Reduction ratio vs consistency for wet grinding of jack pine sawdust at 1000 rpm & approx. 125 kg ODW/h

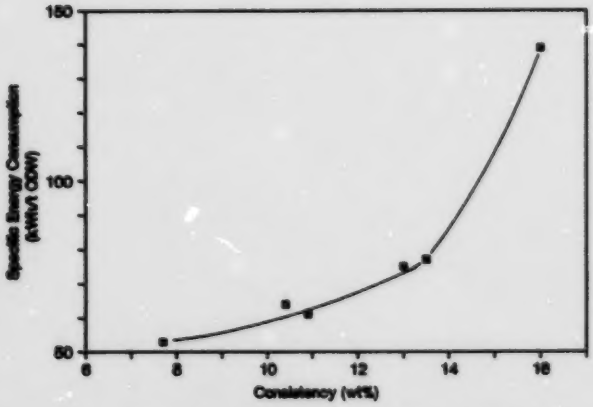


Figure 3 Specific energy consumption vs consistency for wet grinding of jack pine sawdust at 1000 rpm & approx. 125 kg ODW/h

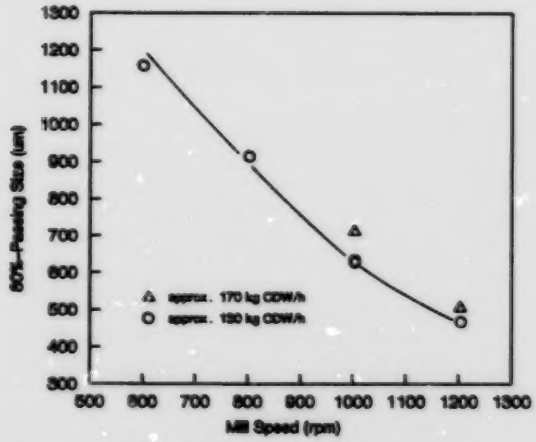


Figure 4 Product size vs mill speed for wet grinding of jack pine sawdust at approx. 11% consistency

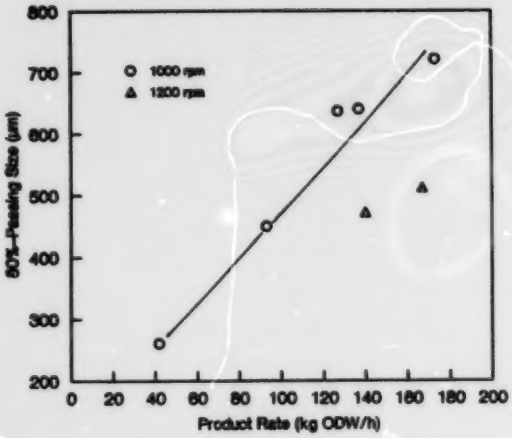


Figure 5 Product size vs product rate for wet grinding of jack pine sawdust at approx. 11% consistency

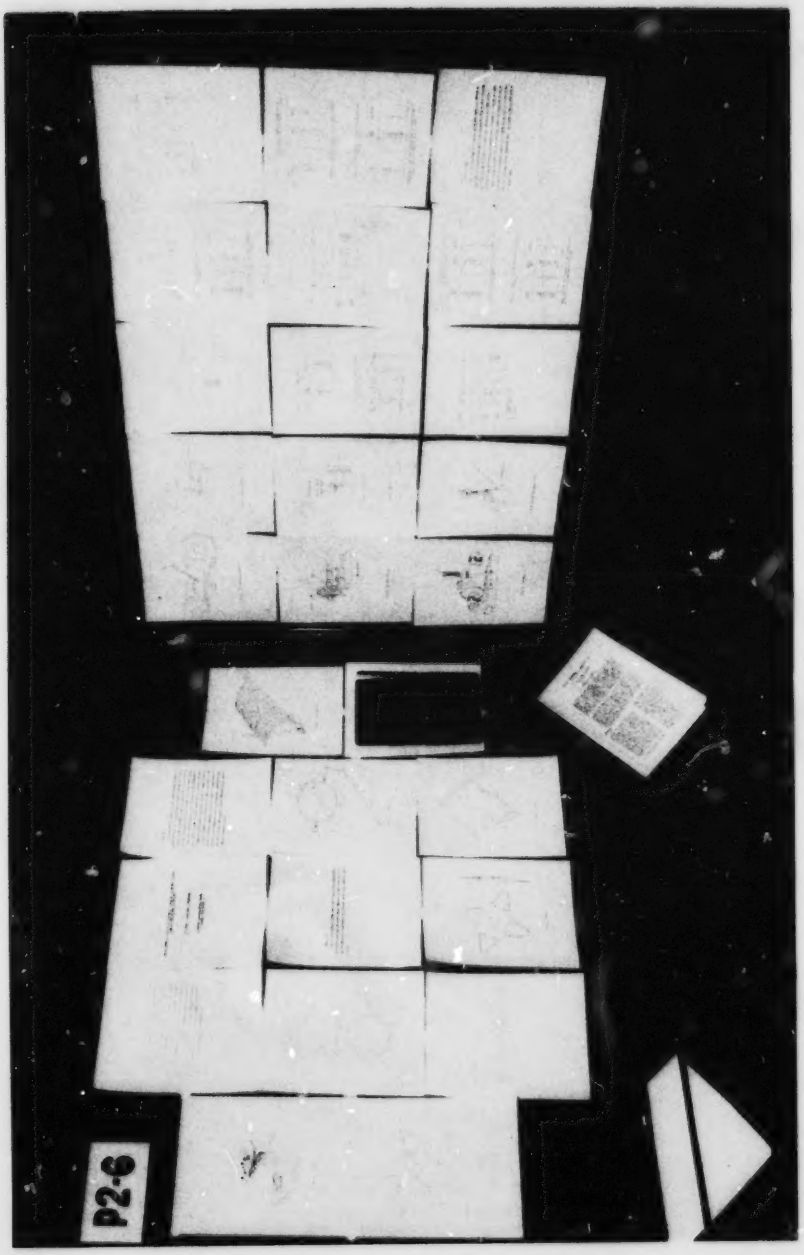
Table 1

Comparison of Performance of Szego Mill and Disk Refiner with Jack Pine Chips

	Szego Mill Product		Disk Refiner Product
Mill Speed (rpm)	1100		1800[2]
	Total	Pulp	
Product Rate (kg ODW/h)	35	28	48
Product Consistency (wt%)	11.1	10.1	Approx. 25
Specific Energy Consumption (kWh/t ODW)	190	240	1030
Product Size by GCI Method:			
d_{50} (µm)	130	150	120
d_{80} (µm)	---	260	330
Product Size by Bauer-McNett Classification:			
d_{50} (µm)	---	190	280
d_{80} (µm)	---	380	640
Work Index ([kWh/s.t. ODW]·$\mu m^{0.5}$)	---	400	1950

Notes: 1. Pulp rate assumed to be total product rate less coarse fraction. Pulp consistency and particle-size distribution measured. Specific energy consumption for pulp calculated from pulp rate and assumption that no mill power is expended on coarse material.

2. Counter-rotating disks - equivalent to 3600 rpm with one disk stationary.


P2-6

DEVELOPMENT AND EVALUATION OF A STRAW CHOPPING SYSTEM FOR FLUIDIZED BED GASIFIERS

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A straw chopping system, designed to provide continuous flow of straw to a fluidized bed gasification system, was constructed and evaluated. The system consists of: a frame, a revolving chute, a cutting drum, a depth of cut controlling mechanism, a concave, an output hopper and a power unit. Chopping of straw must, however, be achieved with the consumption of the least amount of power. This objective was achieved by the proper design of the input hopper to provide a uniform cutting of straw from the bale, the design of the input cutting mechanism with adjustable depth of cut and the correct sizing of the output hopper to provide an efficient removal of the chopped straw. The purpose of this paper is to give detailed descriptions of the design of the straw chopper and to present the performance characteristics of the system as measured by the length of straw, the feed rate and the unit power at various rotational speeds and depths of cut.

Nous avons donc concu, construit et evalue un systeme de hachage de la paille. Ce systeme comprend un bati, une goulotte rotative, un tambour de hachage, un mecanisme permetant de regler la profondeur de coupe, un element concave, une tremie de sortie et un moteur. Le hachage doit, cependant, etre realise en consommant le moins d'energie possible. Dans ce systeme, nous avons atteint cet objectif en coremie d'alimentation de facon a obtenir un hachage uniforme de la paille des balles, en prevoyant un mecanisme ce reglage de la paille des balles, en prevoyant un mecanisme de reglagede la profondeur de couple et en utilisant a la sortie une tremie de taille suffisante pour recevoir la paille hachee. Le but de cette communication est de decrire en detail ce systeme de hachage et de presenter ses caracteristiques de rendement qui sont measurees en termes de la longueur de la paille, de la vitese d'alimentaition et du moteur a differentes vitesses de rottion et a differentes profondeurs de coupe.

INTRODUCTION

Cereal straw, the most abundantly available agricultural crop residue is an excellent fuel for thermochemical conversion (combustion and/or gasification) with relatively low ash content (5%) and high energy content (17.4 gigajoules/tonne). However, the problem often encountered during its use stems mainly from its poor physical form and low bulk density (40-50 kg/m^3). Straw is collected and transported in small bales (46 cm x 48 cm x 70 cm), large cube bales (1.8 m length) or large round bales (1.8 m length x 1.8 m diameter). The direct combustion of the small and large bales has a lower energy recovery efficiency. Dense smoke and particulate emission are always associated with this type of operation. Slag formation occurs as a result of high temperature (1200 - 1400°C) which also causes deterioration of the metal after burner and firebrick lining. In order to maximize the utilization factor and to address the above problem, a fluidized bed gasification system has been developed and used successfully. The system utilizes chopped straw.

The gasification system requires a continuous flow of chopped straw that is consistent in length. Straw, being a highly pliable material, presents difficult conditions in cutting operations and can easily bind up the cuttings edges and stall out the power source. Thus, the chief objective in chopping baled straw is to reduce the material to lengths that can be handled by a screw conveyor. A theoretical cut of 1.5 to 2.0 cm is usually fine enough for gasification purpose. The theoretical length of cut is the amount of advance of the feed mechanism between the cuts of successive knives. It is affected by the cutting speed, the diameter of the holes in the concave and the knives - concave clearance. The cutting energy per ton of straw (hp-h/t) varies with the type of straw, moisture content, type of chopping device and length of cut. Kepner et al. 1977 reported that for given moisture content and theoretical length of cut, the cutting horsepower is directly proportional to the feed rate. Ghaly (1973) studied the effects of rotational speed and concave - hole diameter on the length of straw and the energy of cut. Concaves having hole diameters ranging from 22 mm to 45 mm and rotational speeds ranging from 500 to 1200 rpm (2100 to 5000 m/min) were investigated. The length of straw varied from 2.5 to 6.0 cm. The energy of cut (hp-h/t) remained constant.

Increasing the hole diameter and decreasing the speed increased the length of straw. However, speeds higher than 900 rpm did not significantly reduce the length of straw.

OBJECTIVE

The aim of this study was to design, construct and evaluate a straw chopping system that will chop baled straw and transfer chopped material to the fuel feeding unit and to study the effects of speed and depth of cut on the feed rate, the cutting energy and length of straw.

STRAW CHOPPING SYSTEM

The straw chopping system (Figure 1) was designed for chopping baled straw. The system consisted of (a) a frame, which was used to raise the chopping drum and the hopper to a level where the chopped straw could be easily transported to the straw feeding unit, and provide mounting support for the power supply and the power transmission system, (b) a revolving chute, which was used for the temporary storage and feeding of baled straw to the cutting drum, (c) a cutting unit, which consisted of a cutting drum with rotating blades, a casing, a concave and a hopper (d) a power supply (e) a power transmission system, which consisted of various belts and pullies.

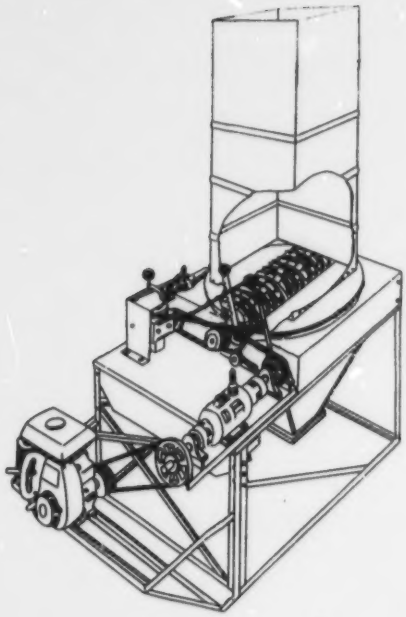

Figure 1. The chopping system

The Frame

The frame (Figure 2) was used to support the cutting drum and rigidly connect the power system with the cutting drum and the chute. It was made of 50.8 mm mild steel angle iron arc welded together. The cross-members of the frame were bolted together using 12.7 mm x 25.4 mm UNC hex head bolts and nuts. The frame consisted of three sections: (a) the primary section, (b) the secondary section (c) the torque meter section.

The primarily section had a rectangular base of 1150 mm x 820 mm and a height of 1320 mm. Two cross braces were bolted onto the uprights of the sides with 19.7 mm x 40 mm hex head bolts and nuts at heights of 1067 mm to 330 mm. The primary section of the frame supported the cutting drum and revolving chute. The secondary section of the frame was an extension of the primary section made of a 650 mm x 820 mm horizontal rectangle bolted onto the vertical uprights at a height of 960 mm. Cross braces were bolted onto the outside of the rectangle section at a height of 50 mm. An additional section was used to support the torque meter sensor and the necessary couplings and bearings. This section was made of 75 mm wide x 35 mm deep channel iron and was supported on the outside by a mild steel square bar of 30 mm x 30 mm and on the inside by the upper edge of the primary section. The square bar was supported on the lower side by the secondary section of the frame.

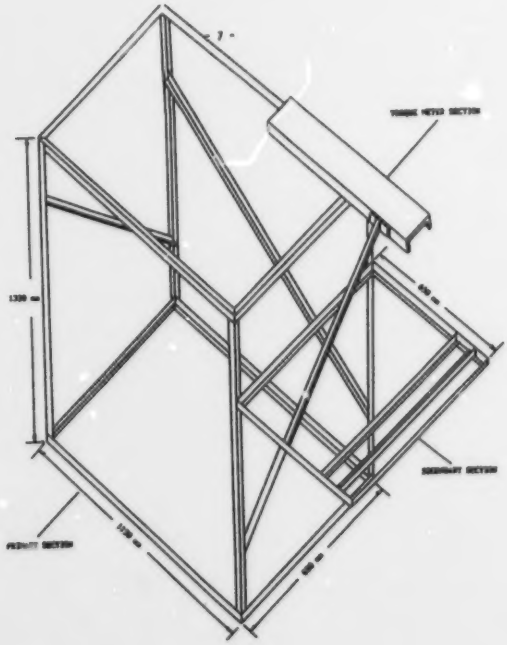

Figure 2. The frame

The Revolving Chute

The chute (Figure 3) was made of a large open ended box with a cross-section of 420 mm x 520 mm and a height of 1520 mm. The box was constructed of 16 gauge galvanized steel. It was used to house 2 small bales of straw above the cutting drum. The two bales of straw in the chute created a downward force which kept the straw in contact with the cutting blades. A large circular plate of 4 mm thickness and 730 mm diameter was arc welded to the bottom of the box. The circular plate had a 40 mm wide flange welded underneath its outer edge.

The Cutting Unit

A solid round bar of 30 mm diameter and 840 mm length was used to support 16 cutting blades (Figure 4). The shaft was supported by a slip bearing at each end. The first blade arm was located 180 mm from the driven end of the blade shaft, with the other 15 arms located at 35 mm intervals. The arms were arc welded onto the shaft whereas the blades were connected to the arms by 12.7 mm x 20.0 mm hex head bolts and nuts (Figure 5). The arms were made of mild steel circular plates of 5 mm thick and 140 mm diameter. The blades were made of high tensile steel and were 80 mm long, 80 mm wide at the base and 20 mm wide at the tip. A driven pulley of a 135 mm diameter was fastened to the blade shaft by a 5 mm x 5mm key. A drive pulley of 100 mm diameter was mounted outboard of the blade shaft driven pulley and was used to supply power to the revolving chute. The drive pulley was fastened to the blade shaft by a 5 mm x 5 mm key.

The casing of the cutting drum (Figure 6) was a 230 mm high x 800 mm wide x 730 mm long mild steel box with two small rectangular openings on the upper surface was 250 mm x 670 mm. It was centered in a circular ring 700 mm diameter and 35 mm height. A wide teflon strip was connected to the circular ring with 18 flush mount 10 mm x 15 mm machine screws. The opening on the lower surface was 250 mm x 670 mm. A concave having 12 mm diameter holes was connected to the casing under the cutting drum. The knives-concave clearance was 25 mm at the front and 12 mm at the back. A large galvanized sheet metal hopper was connected to the bottom of the cutting drum casing. The hopper was 670 mm x 560 mm at the top and 305 mm x 305 mm at the bottom with a height of 340 mm (Figure 7). A sliding door (305 mm x 360 mm) located at the bottom of the hopper was used to empty the hopper.

The theoretical length of cut was varied by the movement of a restricting grate in relation to the blades. The restricting grate (Figure 8) consisted of 16 prongs welded to an end bar. Each prong was 295 mm long, 10 mm wide and 10 mm thick. The prongs formed an arc around the rotating blades. A notched arm connected directly to the end bar of the arced grate was used to allow more or less straw to come in contact with the blades.

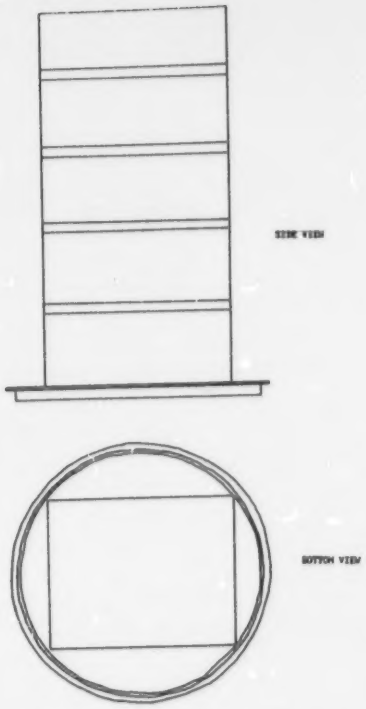

Figure 3. The revolving chute

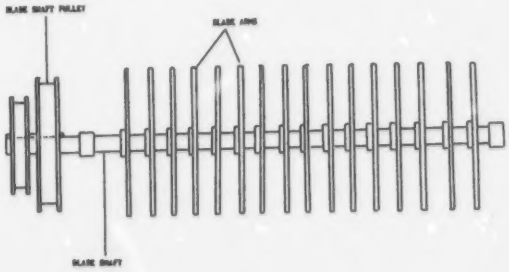

Figure 4. The blade shaft

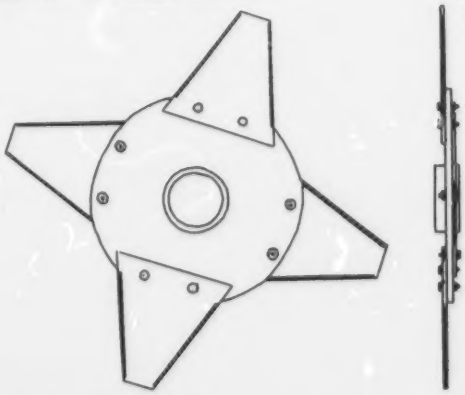

Figure 5. The blades

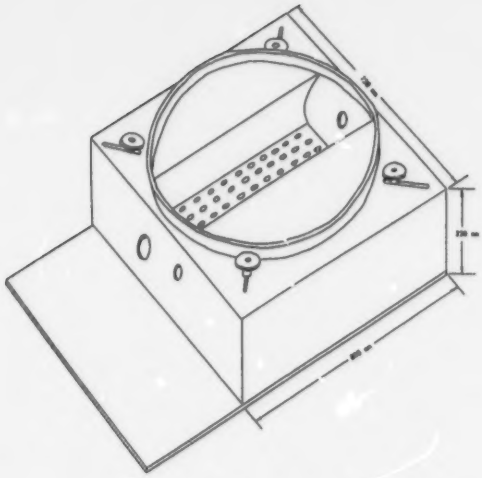

Figure 6. The casing of the cutting drum

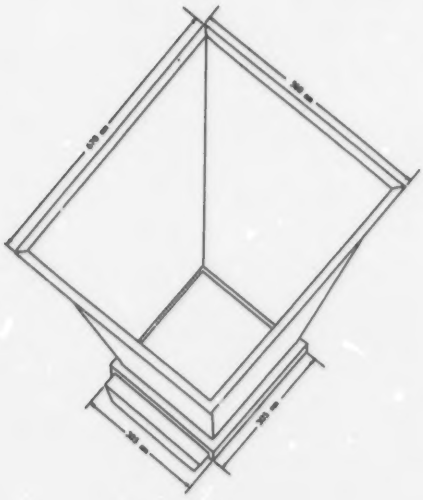

Figure 7. The bottom hopper

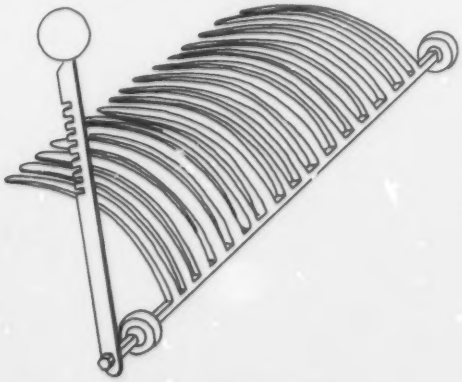

Figure 8. The restricting grate

The Torque Sensor

A torque meter sensor (Intertechnology 1105 - 10K) was utilized to measure the torque output of the engine. The signal from the sensor was transmitted to a dial (Vishay Instruments Bridge Amp meter) to give a scale reading. The sensor (Figure 9) was rigidly mounted on the channel section iron with four 14.3 mm x 45 mm hex head nuts and bolts. Two couplings (Lovejoy L110 I.500) were used to connect the torque meter sensor shaft to the torque meter input and output shafts. The two couplings were connected to the torque meter sensor input and output shafts with two 5 mm x 5 mm keys. The torque meter input and out shafts were supported by 2 non expansion, 2-bolt pillow blocks each. The pillow blocks were bolted onto 41 mm horizontal angle iron support using two 14.3 mm x 50.4 mm UNC hex head bolts and nuts. The horizontal angle iron support was arc welded onto the channel section of the frame. The pulley on the output shaft (Figure 10) had a 100 mm diameter while the diameter of the pulley on the input shaft (Figure 11) was varied to provide various blade shaft rotational speeds.

The Power Unit

The power unit was used to rotate the blades and the revolving chute. An 8 hp, 4- stroke, single cylinder gasoline engine was used as a power supply. The engine was mounted on a moveable platform on the secondary frame section. It was fastened onto the platform with 20 mm x 45 mm hex head nuts and bolts. A 115 mm diameter pulley with a 15 mm deep groove was connected to the 25 mm diameter output shaft of the engine. A 5 mm x 5 mm key prevented the pulley from rotating on the shaft.

The Power Transmission System

A 450 mm rubber belt was used to connect the engine pulley to the pulley on the torque meter input shaft. Another 760 mm rubber belt was used to connect the pulley on the torque meter output shaft to the pulley on the blade shaft. An engaging/disengaging mechanism made of 90 m diameter idler pulley and lever arm was used to engage and tighten the belt around the pulleys of the blade and torque meter shafts (Figure 12).

A 910 mm belt was used to connect the outboard pulley on the blade shaft to a small input pulley on the transfer case of the chute which was used to change the plane of motion from vertical to horizontal. The transfer case consisted of an input pulley, a gear set and an output pulley (Figure 13). The gear set consists of two bevel gears which operated at a 90°C angle, with the vertical gear connected to the pulley and the horizontal gear connected to the output pulley. To rotate the revolving chute, a 2800 mm rubber belt was used to connect the flange of the revolving chute and the small output pulley on the transfer case. A clutch system (Figure 14) consisting of a 90 mm diameter idler pulley and an engaging/disengaging arm, allowed the starting and

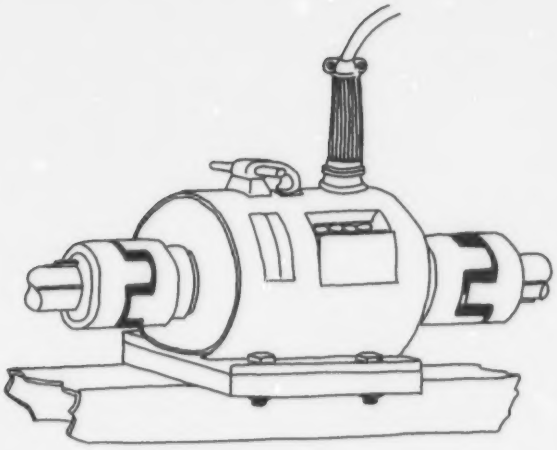

Figure 9. The torque meter

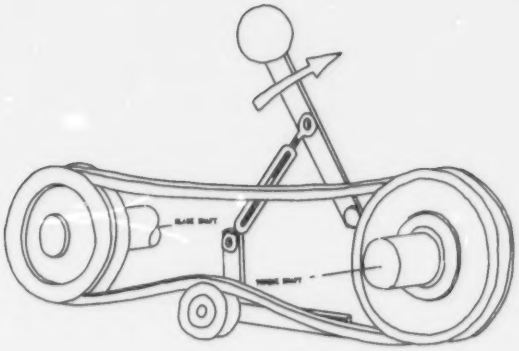

Figure 12. The blade shaft engaging mechanism

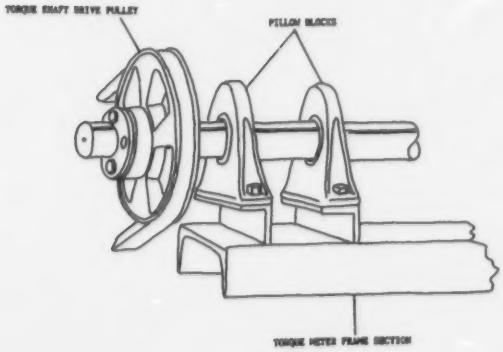

Figure 10. The torque meter input shaft

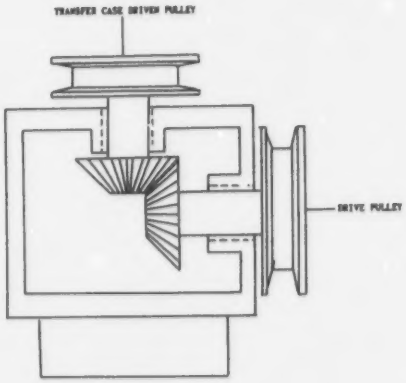

Figure 13. The chute transfer case

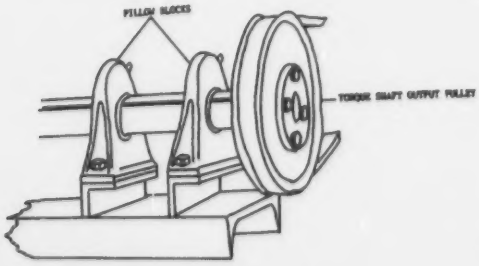

Figure 11. The torque meter output shaft

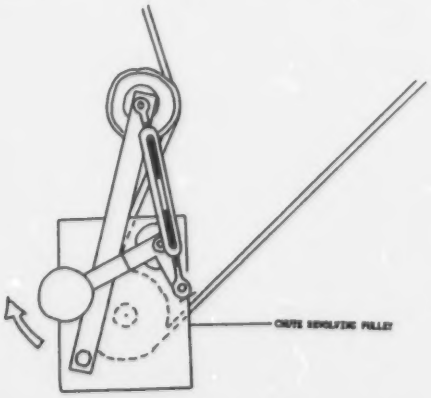

Figure 14. The chute engaging mechanism

stopping of the revolving chute.

Four idler wheels (Figure 15) made out of hardened rubber were bolted to the top of the casing to keep the revolving chute in line with the circular ring on the top of the cutting drum. The idler wheels were fastened using 20 mm x 75 mm hex head bolts and nuts. A belt guide was added to each bolt to prevent the belt from running off the edge of the plate. Each guide was made of a 60 mm x 25 mm mild steel piece of 3 mm thickness, bent 90o to form two 30 mm x 25 mm rectangles. One side of the guide was mounted on the bolt under the idler wheel, and the other side was pointed up towards the centre of the lower surface of the idler wheel.

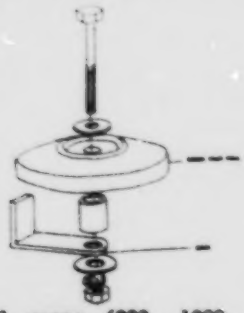

Figure 15. An idler wheel

EXPERIMENTAL DESIGN

Seven blade rotational speed (800, 1000, 1250, 1400, 1750, 2000 and 2500 (rpm) were investigated. This allowed a cuting velocity in the range of 12.56 to 39.25 m/s. For each blade speed, 7 theoretical lengths of cut (3.9, 8.2, 12.1, 16.7, 21,8, 27.0 and 32.0 mm) were carried out. Three replicates were carried out for each length of cut - blade speed combination. This resulted in 147 experimental runs.

EXPERIMENTAL PROCEDURE

Testing Protocol

Two bales of straw were placed in the revolving chute and the baling wires were removed. The pulley of the torque meter input shaft was changed to give the required blade shaft speed. The engine output pulley was connected to the torque meter input pulley with a rubber belt. The belt tension was adjusted by moving the enginemounting platform. The depth of cut controlling lever arm was then placed on the selected notch. The blade shaft pulley was disengaged using the engaging/disengaging mechanism. The engine was then turned on and the throttle was opened to increase the engine speed to 300 rpm. The blade shaft pulley and revolving chute were then engaged by moving their respective engaging arms. The blade shaft rotational speed was fine tuned using the engine throttle. The hopper door was then closed and the stopwatch was started. A large extra heavy duty trial plastic bag, labelled with the blade speed, the notch number and the trial number was then placed under the hopper. The hopper door was reopened and the experimental run lasted 2 minutes. Ten readings each were taken of the blade shaft speed, the torque meter input shaft speed and the torque meter sensor scale during the 2 minute period of each experimental run.

The blade shaft pulley was then disengaged and the chute refilled with two bales. The notch selection lever arm was then moved up one notch and the test procedure was repeated. The test was repeated three times for all notches. The torque meter input shaft pulley was changed and the above procedure was repeated. The weight of the trial bag was recorded for feed rate computation. A sample of the output chopped straw was retained and the rest of the straw was disposed off.

Straw Particle Size Distribution

Samples of the chopped straw were collected randomly for sieve analysis to determine the size distribution (length, width and weight fractions) of straw particles. An electrical sieve shaker (Hoskin Scientific Limited), driven by a 0.25 hp electric motor running at 1725 rpm, was used. The shaker contained six standard sieves and a bottom pan whose specifications are given in Table 1. The sieves were arranged according to the size of their openings. The bottom pan was placed under seive No. 6 and designated sieve No. 7. The system of seives was placed onto the electrically operated sieve shaker. A sample of the chopped straw was weighed and put into sieve No. 1 which was then covered with the seive lid. The shaker was operated for 30 minutes. The chopped straws, collected in each seive, were then analyzed for weight, length and width distribution.

Table 1. The sieve opening size

Sieve Number	Mesh Number	Opening Size (mm)
1	4	4.7600
2	8	2.3800
3	14	1.4100
4	30	0.5950
5	50	0.2990
6	100	0.1490
7	pan	0.0000

RESULTS AND DISCUSSIONS

Length of Straw

The chopped straw was analyzed for weight, length and size distribution using an electric shaker with 6 sieves and bottom pan. A sample of the results of an experimental run is shown in Table 2. The sample whose analyses are reported was collected at the third trial of the 800 rpm and notch number 4 (1.2 cm) combination. The length of the straw collected in sieve 1 varied

from 8 mm to 86 mm with an average length of 42.6 mm, most of the straw were between 30 and 59 mm in length. The width of the straw varied from 1.5 mm to 7 mm with an average width of 3.8 mm, most of the straw were between 4 and 5 mm in width. Most of the straw collected in sieve 1 were not sheared longitudinally and had nodes.

Table 2. Straw Weight, Length and Width Distribution for a Typical Experimental Run

Sieve Number	Straw (%)*	Length (mm) Range	Length (mm) Average	Width (mm) Range	Width (mm) Average
1	2.90	30.0-59.0	42.6	3.0-5.0	3.8
2	33.39	10.0-35.0	22.5	2.0-3.0	2.6
3	35.01	3.0-19.0	13.3	1.5-2.0	1.7
4	26.30	2.0-13.0	9.0	1.0	1.0
5	7.55	1.1- 5.0	2.0	0.2	0.2
6	4.85	0.1- 2.0	0.5	0.1	0.1
7	0.80	dust	dust	dust	dust

* Percent of the total weight.

The length of the straw collected in sieve 2 varied from 3 mm to 50 mm with an average length of 22.5 mm, most of the straw were between 10 and 35 mm in length. The width of the straw varied from 1 mm to 4 mm with an average width of 2.6 mm, most of the straw were about 3 mm in width. Most of the straw collected were halved longitudinally. Many nodes were collected in this sieve but they were smaller in width and shorter in length as compared to those collected in sieve 1.

The length of the straw collected in sieve 3 varied from 3 mm to 38 mm with an average length of 13.3 mm, most of the straw were between 3 and 19 mm in length. The width of the straw varied from 1 mm to 3 mm with an average width of 1.7 mm, most of the straw were about 2 mm in width. Most of the straw resulted from about 3 times longitudinal shearing of the straw stem.

The length of the straw collected in sieve 4 varied from 2 mm to 19 mm with an average length of 9.0 mm, most of the straw were between 2 and 13.3 mm in length. The width of the straw varied from about 0.2 to 2 mm with an average width of 1 mm, most of the straw were about 1 mm in width. Most of the straw resulted from about 5 to 10 times longitudinal shearing of the straw stem.

The length of the straw collected in sieve 5 varied from about 0.5 to 20 mm with an average length of 2.0 mm, most of the straw were between 1 and 5 mm in length. The width of the straw varied from very minute particles to about 0.3 mm with an average width of about 0.2 mm, most of the straw were about 0.2 mm in width.

The length of the straw collected in sieve 6 varied from very tiny particles (about 0.1 mm) to 10 mm with an average length of 0.5 mm, most of the straw were between 0.1 and 2 mm in length. The width of the straw varied from very minute particles to about 0.1 mm with an average width of about 0.1 mm, mot of the straw were about 0.1 mm in width. Fine fluffy dust with straw fibres of about 3 mm and about 0.05 mm in width were collected in the bottom pan. The dust made up most of the contents of this pan.

In general there was more variation in the length of the straw collected in each sieve than the width. Most of the strw (85-90%) was collected in sieves 2, 3 and 4. The weighed average of the length of the straw values of each sieve. Analysis of variance was performed on the length of straw data as shown in Table 3. Ducan Multiple Range Test was also performed on the data (Tables 4 and 5) to test the differences among the means. Both the theoretical length of cut and the cutting speed significantly affected the length of straw. The length of straw varied from 14.19 to 18.85 mm depending on the length of cut and rotational speed.

Table 3. Analysis of variance of the length of straw data

Source	DF	SS	MS	F	P > F
TOTAL	146	647.36			
MODEL	48	568.74	11.49	14.77	0.0001
L	6	30.19	5.03	6.27	0.0001
S	6	447.54	74.59	92.97	0.0001
L*S	36	91.01	2.53	3.15	0.0001
ERROR	98	78.62	0.80		

L = length of cut (cm)
S = speed (rpm)
R^2 = 0.72
CV = 8.89%

Table 4. Mean values of straw length as affected by the theoretical length

Length of Cut (mm)	N	MEAN (mm)	GROUPING
3.9	21	17.20	A
8.2	21	16.87	A
16.7	21	16.73	AB
21.8	21	15.82	BC
27.0	21	15.52	BC
32.0	21	15.82	C

Means with the same letters are not significantly different from one another at 0.05 level.

Table 5. Mean values of straw length as affected by speed

Speed (rpm)	N	MEAN (mm)	GROUPING
800	21	18.85	A
1000	21	17.95	B
1250	21	16.57	C
1400	21	16.17	C
1750	21	16.07	C
2000	21	14.94	D
2500	21	14.19	D

Means with the same letters are not significantly different from one another at 0.05 level.

Feed Rate

The straw chopper output was calculated at various theoretical lengths of cut and cutting speeds. An analysis of variance was performed on the data shown in Table 6. Duncan Multiple Range Test was also performed on the data to test the differences among the means as shown in Tables 7 and 8. Both the theorectical length of cut and cutting speed had significant effects on the feed rate. Increasing the lenght of cut and and/or the speed increased the feed rate. The values ranged from 1.48 to 10.52 kg/minute depending on the length of cut and speed used.

Table 6. Analysis of variance of the feed rate data

Source	DF	SS	MS	F	P > F
TOTAL	146	1515.77			
MODEL	48	1442.65	30.06	40.28	0.0000
L	6	106.09	17.68	23.70	0.0001
S	6	1183.20	197.20	264.29	0.0000
L*S	36	153.36	4.26	5.71	0.0001
ERROR	98	73.12	0.75		

L = length of cut (cm)
S = speed (rpm)
R^2 = 0.95
CV = 1.724

Table 7. Mean values of feed rate as affected by the theoretical length of cut

Speed (rpm)	N	MEAN (kg/min)	GROUPING
800	21	1.48	A
1000	21	2.37	B
1250	21	3.43	C
1400	21	4.80	D
1700	21	5.53	E
2000	21	6.94	F
2500	21	10.52	G

Means with the same letters are not significantly different from one another at 0.05 level.

Table 8. Mean values of feed rate as affected by the speed

Speed (rpm)	N	MEAN (mm)	GROUPING
800	21	1.48	A
1000	21	2.37	B
1250	21	3.43	C
1400	21	4.80	D
1750	21	5.53	E
2000	21	6.94	F
2500	21	10.52	G

Means with the same letters are not significantly different from one another at 0.05 level.

Energy of Cut

The effects of both the theoretical length of cut and cutting speed on the energy of cut were investigated. An analysis of variance was performed on the data as shown in Table 9. Duncan Multiple Range Test was also performed on the data to test the differences among the means as shown in Tables 10 and 11. Both the theoretical length of cut and speed had significant effects on the power required for cutting the straw. However, the power required for cutting the straw varied only from a low of 3.69 hp to a high of 5.02 hp (36%) on the average when changing the length of cut from 3.9 mm to 32.0 mm (720%). The power required to cut the straw varied from a low of 1.76 hp to a high of 7.76 hp (340%) on the average when changing the speed from 800 rpm to 2500 rpm (212%).

Table 9. Analysis of variance of the horse power data

Source	DF	SS	MS	F	P > F
TOTAL	146	647.36			
MODEL	48	568.74	11.49	14.77	0.0001
L	6	30.19	5.03	6.27	0.0001
S	6	447.54	74.59	92.97	0.0001
L*S	36	91.01	2.53	3.15	0.0001
ERROR	98	78.62	0.80		

L = length of cut (cm)
S = speed (rpm)
R^2 = 0.88
CV = 20.30

CONCLUSIONS

Both the theoretical length of cut and the cutting speed significantly affected the length of straw, the straw feed rate and the power required for cutting the straw. Increasing the theoretical length of cut and or the cutting speed decreased the length of straw, increased the straw feed rate and increased the power consumption. Although, the length of straw decreased only from 18.85 mM to 14.19 mm, which is not significant, the energy of cut (hp.h/t) was substantially

improved by increasing the speed due to increases in the feed rate. It was reduced from 14.04 to 8.20 hp.h/t. The energy cut was less than 0.2% of the energy content.

Table 10. Mean values of power consumption as affected by the theorectical length of cut.

Length of Cut (cm)	N	MEAN (hp)	GROUPING
3.9	21	3.69	A
3.2	21	4.31	AB
12.1	21	4.45	C
16.7	21	5.02	C
21.8	21	5.01	C
27.0	21	4.45	C
32.0	21	4.27	B

Means with the same letters are not significantly different from one another at 0.05 level.

Table 11. Mean values of power consumption as affected by speed.

Speed (rpm)	N	MEAN (hp)	GROUPING
800	21	1.76	A
1000	21	2.97	B
1250	21	3.87	B
1400	21	4.58	B
1750	21	4.89	C
2000	21	5.07	D
2500	21	7.76	E

Means with the same letters are not significantly different from one another at 0.05 level.

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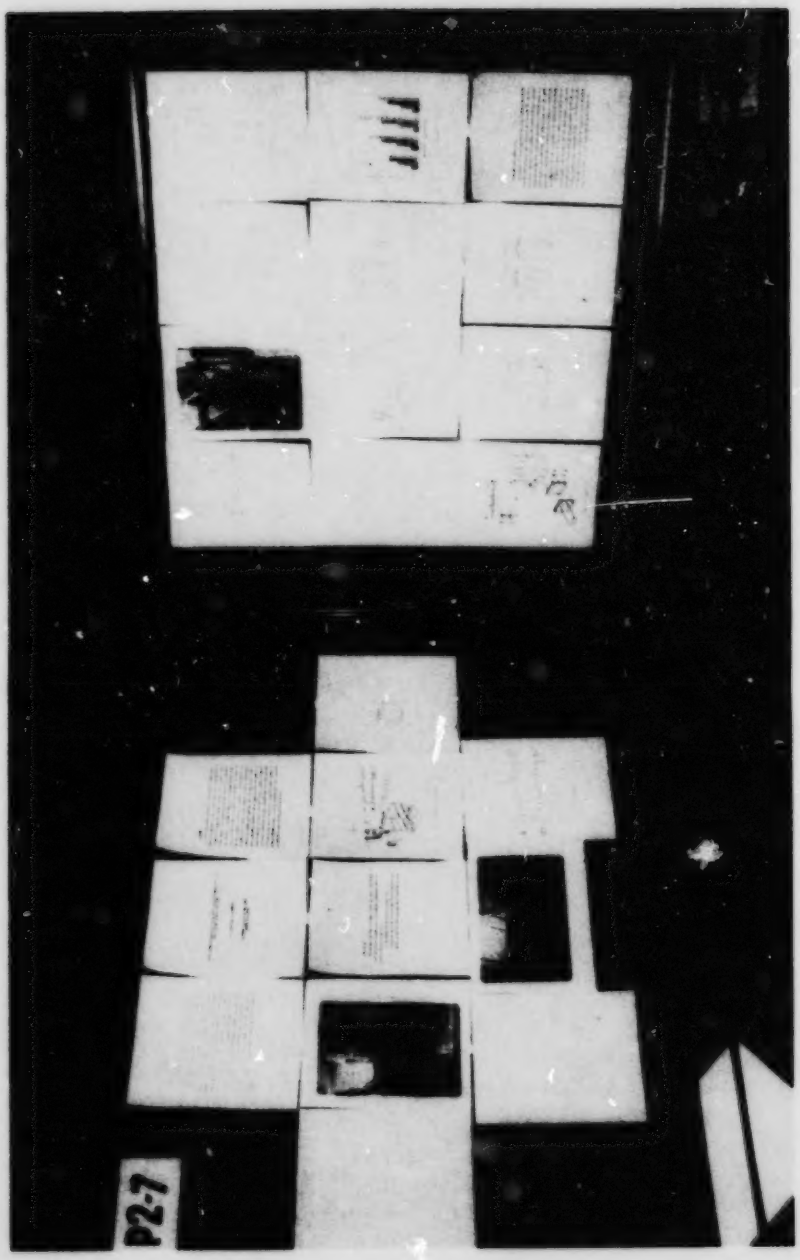
P2-7

DEVELOPMENT AND EVALUATION OF A STRAW FEEDING SYSTEM FOR FLUIDIZED BED GASIFIERS

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For continuous operation of the gasifier, straw must be chopped and fed continuously to the system. However, straw, being a highly cohesive material, presents difficult flow conditions in hoppers and ducts. Such materials easily create funnel flow and piping conditions. This occurs when the pressure of the material above an impending dome of material is too small, thus a stable dome forms resulting in blockage of the discharge. In addition, once the flow of the straw is interrupted by build-up along the flow channels, pressure builds up and the straw becomes progressively compacted into a dense structure. A straw feeding system has, therefore, been designed, constructed and evaluated. It consisted of: a frame, a hopper, an auger, two agitators, a drive system and a power unit. In order to achieve good flow conditions, the hopper must operate under "mass outflow" and the material should not be allowed to build up along the flow channels. These objectives have been achieved by the proper design of the hopper configuration, the installation of agitators in the hopper and use of an auger in the outlet duct leading into the gasifier.

Pour que le gazeificateur fonctionne en continu, la paille doit entre hachee et alimentee en continu dans le systeme. Toutefois, comme la paille a fortement tendance a s'agglomere, son passage dans le systeme de hachage et dans les conduites presente certaines difficultes. Ce type de materiau peut facilement donner lieu a un ecoulement de type "entonnoir" et a du "renardage". On observe ce type d'ecoulement lorsque la pression exercee sur les dess d'un dome est tres faible; il se forme alors un dome stable qui interrompt l'ecoulement. De plus, des que l'ecoulement a ete interrompu par une accumulation dans les conduites, la pression augmente et la paille est progressivement transformee, par tassement, en une masse dense. On a donc concu, construit et evalue un systeme d'alimentation comprenant un bati, une tremie,une sonde, deux agitateurs, un systeme d'entrainement et un moteur. Pour obtenir de bonnes conditions d'ecoulement, on doit pouvoir observer le rejet d'une grande quantite de paille dans la tremie, et la paille ne doit pas s'accumuler dans les conduites. On a atteint ces objectifs en donnant a la tremie la configuration appropriee, en installant des agitateurs dans celle-ci et en utilisant une sonde dans la conduite de sortie menant au gazeificateur.

INTRODUCTION

Straw is a plant residue of grain crops such as wheat, rice, barely, rye and oats. The production of straw in Canada is over 60 million tonnes per year. A significant part of the produced straw (60-80%) can be made available for energy recovery through combustion and gasification processes to meet demands for space and water heating, grain drying and for operating small stationary machines on Canadian farms.

Because of a wider range of applications of the gasification products, a concerted effort has been made to develop reactors suitable for gasification of straw. A gasification system, designed to utilize a particulate biomass such as chopped straw, requires a continuous flow of the fuel material at a constant rate. This can be accomplished by a feeding system that consists of a hopper for holding sufficient quantity of straw and a handling mechanism for continuous extraction of straw from the hopper and simultaneous deposition of straw into the reactor.

OBJECTIVES

The main aim of this study was to design, construct and evaluate a straw feeding system that will feed the chopped straw into a fluidized bed gasification system. The specific objectives of this paper are:

(a) to present detailed descriptions of the straw feeding system, and
(b) to present the results of the straw flow output of the feeding system at different auger/agitators speeds

STRAW FEEDING SYSTEM

The Straw Feeding System (Figure 1) was designed for feeding chopped straw into a fluidized bed gasification system. It consists of (a)a frame, which is used to raise the hopper above the auger, support the auger and agitators and provide a rigid mounting for the power system; (b) a hopper, which serves as a holding container and chute for chopped straw; (c) two agitators, which are made of steel rods with wire spikes extending from them to loosen and mix the straw, (d) an auger, which is a simple screw used for moving the straw from the hopper to the gasifier; (e) a reducer assembly, which is used to compact the straw at the end of the auger housing to avoid back flow of hot gases and to feed the compacted material into the gasifier, and (f) a drive system, which consists of an electric motor, a speed controller and various chains and sprockets.

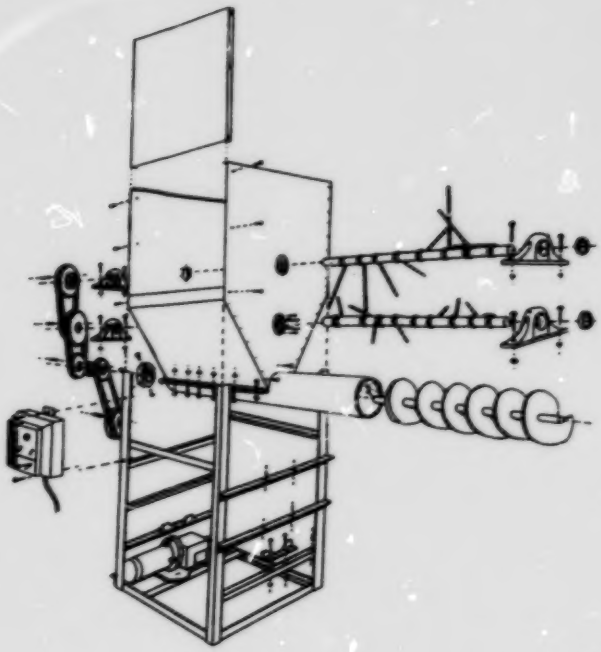

Figure 1. The straw feeding system

The Frame

The frame (Figure 2) is a structural arrangement of angle iron used to position the hopper over the auger and to support and align the auger and agitators. The frame was designed in such a way that the hopper assembly can slide in and out for easy evaluation and modification. The main frame was made of 50.8 mm mild steel angle iron. The supports for the agitators and auger were made of 41.0 mm mild steel angle iron. The base of the frame was 610 mm x 500 mm and the height was 1210 mm. The angle iron of the main frame section, which form the rectangular housing portion of the hopper, were single fillet arc-welded together. The cross-sectional pieces were bolted onto the main frame using two 12.7 mm x 25.4 mm UNC bolts and hex nuts on each end. The supports of the auger, lower agitator and upper agitator were located on the front and back of the frame at heights of 325 mm, 505 mm, and 675 mm, respectively. Additional frame reinforcements were made of 41.0 mm mild steel angle iron arc welded with single fillets and located on the sides of the frame at a height of 750 mm.

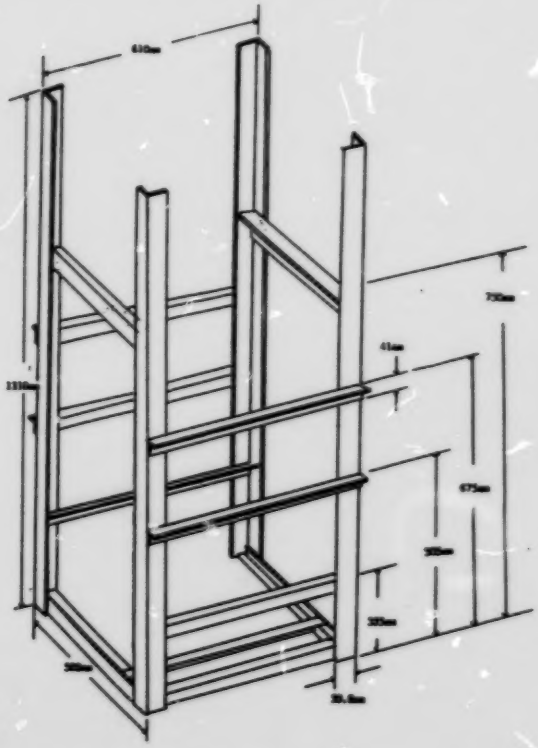

Figure 2. The supporting frame

The Hopper

The hopper (Figure 3) is a funnel shaped reservoir from which the straw is discharged into an auger located at its base. It was made of 6 pieces of 18 gauge galvanized sheetmetal. The upper section of the hopper resembles a cube having dimensions of 500 mm, 490 mm and 590 mm for the depth, length and width, respectively. Three of the sides were pop riveted together using sixteen 9.5 mm pop rivets, spaced 75 mm apart. The fourth side (removable section) was held in place with 6 machine screws, 3 placed equidistant on each end. The lower section of the hopper resembles a prism having dimensions at the bottom end of 505 mm, 490 mm and 590 mm for the depth, length, and width, respectively. The angle of inclination of the lower section of the hopper was 28° to vertical. Where the lower section of the hopper connects with the auger housing, the

sheetmetal was flared out to form a flange where eight 12.6 mm holes were spaced evenly on each flange. To connect the auger casing to the front and back of the hopper, 3 evenly spaced 7.4 mm x 24.5 mm cap screws and hex nuts were used at each end. Seal supports were placed where the agitators enter and exit the hopper to seal the circular opening. These were held in place with six 6.4 mm x 25.4 mm cap screws and hex nuts.

The Agitators

The agitators were found necessary to prevent the straw from settling and consolidating to form a bridge. They were used to loosen the straw and mix it to keep the fuel supply homogeneous and consistent. Two agitators were made of 25.5 mm diameter steel shafts(Figure 4) with wire wrapped around them 4 turns and extended to form spikes (Figure 5). There were small holes drilled in each shaft for the wrapped ends of the wires, to prevent them from rotating around the shaft. As the force of resistance of the straw tries to wrap the wires around the shaft the wires tighten themselves onto the shaft. The upper agitator had 8 music gauge wires extending 170 mm radially whereas the lower agitator had 9 music gauge wires extending 80 mm radially. To support the shafts at each end, non-expansion 2-bolt pillow blocks (lubricated with grease) were utilized. These pillow blocks were bolted onto horizontal angle iron supports using two 14.3 mm x 50.4 mm UNC bolts and hex nuts each.

The Auger

The auger system (Figure 6) consists of the auger screw and housing. The auger screw was made of 8.5 mm thick stainless steel flighting which was tig welded to a 1200 mm long, 316 stainless steel shaft of 30 mm diameter. The pitch of the flighting was 150 mm. The auger was a 1000 mm long single thread right hand design. The driven end of the auger, which rotates in a double row angular contact thrust bearing, was connected to the auger housing by four 12.5 mm x 25.4 mm UNC bolts and hex nuts to prevent the auger from sliding out of alignment. The output end of the auger rotates freely inside of the auger housing. The auger rotates with a clearance of 5 mm and 0.001 mm on the top and bottom, respectively. The housing for the auger was made of stainless steel cylinder of 10 mm thick wall and 95 mm diameter. The section under the hopper was split length-wise horizontally with 4 steel flanges arc welded onto the cylinder for connection with the hopper as shown in Figure 7.

The Reducer Assembly

A combination of various elbows and reducing elbows of varying dimensions were investigated in relation to straw compaction at the end of the auger housing. The aim was to arrive at a proper design of a reducing elbow that will provide straw compaction enough to stop the flow of hot gases from the gasifier into the feeding system, and that which would consume the least energy. The

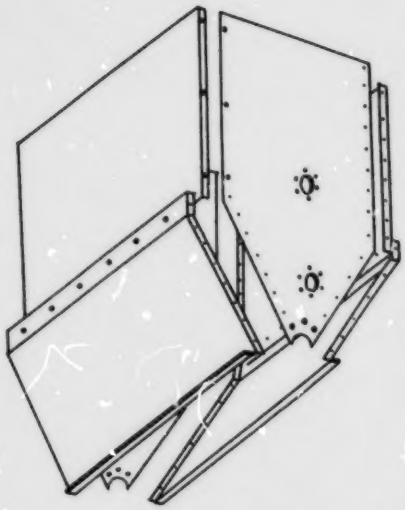

Figure 3. The hopper

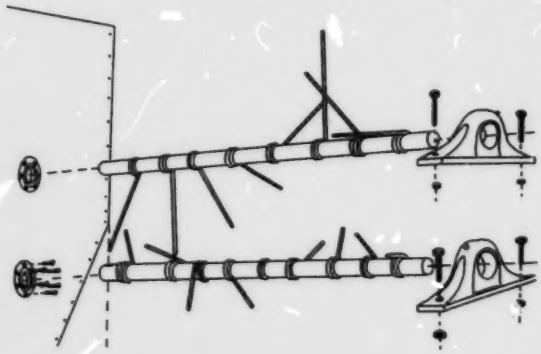

Figure 4. The agitators

Figure 5. A wire spike

final design of the selected reducing elbow is shown in Figure 8. It consists of a 90° reducing elbow of 95 mm diameter at the horizontal end (auger end) and 78 mm diameter at the vertical end (distributor plate end). The auger end was connected to the auger housing by four 12.5 mm x 50.8 mm UNC bolts and hex nuts through square flanges of 157 mm x 157 mm. The vertical end was tig welded to the distributor plate.

The Drive System

The drive system consists of a motor, a speed controller and various chains and sprockets. The motor used to drive the agitators and the auger is a continuous duty, 3/4 hp motor (Honeywell field Model No.SR3736-3162). This motor was mounted on the base of the main frame solidly with four 1.4 mm x 25.5 mm UNC bolts and hex nuts. The motor speed was controlled by a speed controller (Browning Model LWS 25/200) connected in series between the 115 volt power source and the motor (Figure 9). This controller allowed the angular speed of the auger to be varied, in increments, from 0 rpm to 60 rpm. The sprockets and roller chains, which connect the motor with the auger and agitators, were number 40 (13 mm pitch). The sprockets are made of steel with hardened teeth and run with a light lubricant from the chain. The sprockets are prevented from rotating on the shafts by using keys made of 5.0 mm x 5.0 mm keystock and keyways. The sprockets were arranged (in the initial design) so as to give a 1:1 speed ratio from the motor to the auger, a 5:1 speed ratio from the auger to the lower agitator, and a 3:1 speed ratio from the lower agitator to the upper agitator as shown in Figure 10.

Figure 6. A cross section of the auger screw and housing

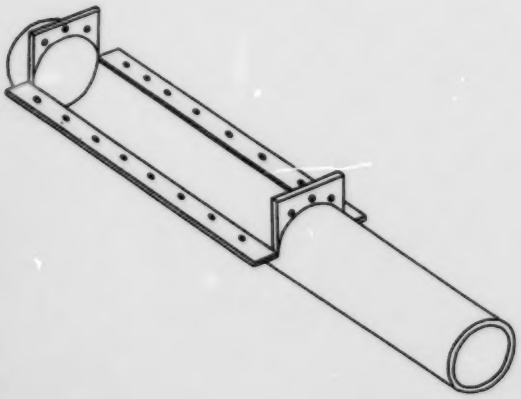

Figure 7. The auger housing

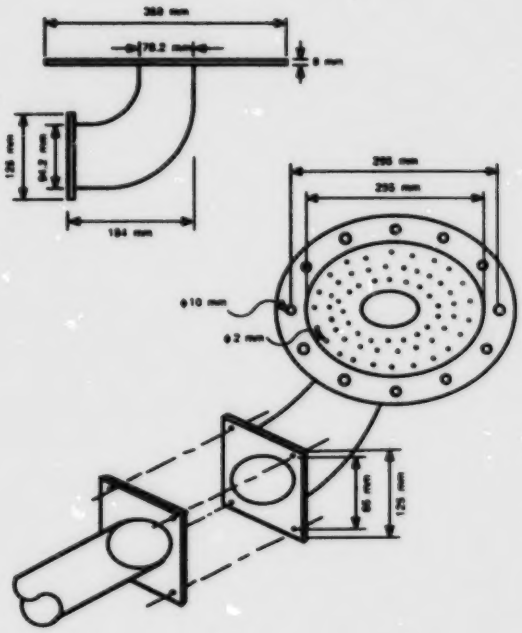

Figure 8. The reducer assembly

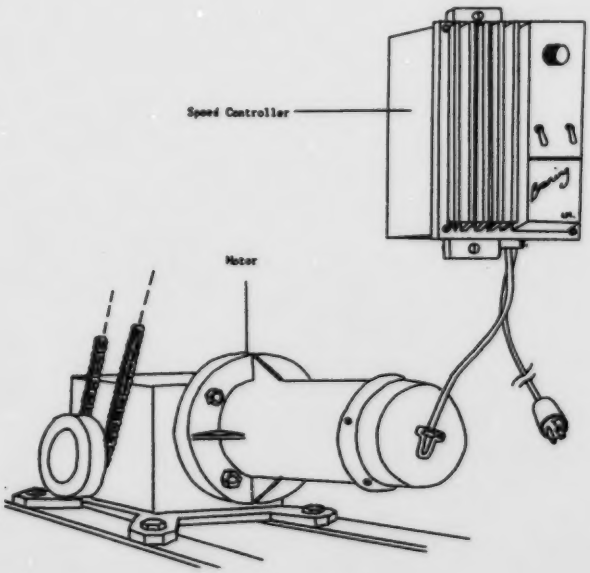

Figure 9. The motor and speed controller

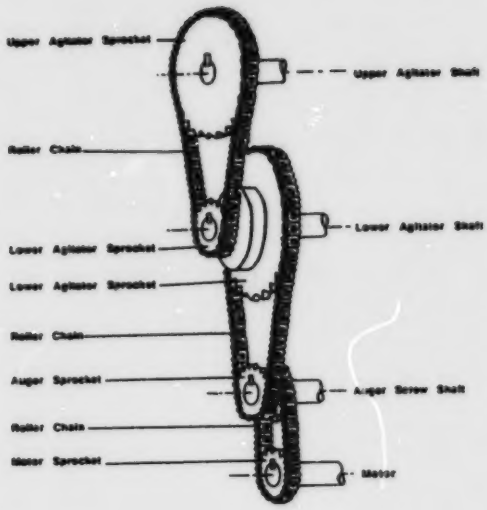

Figure 10. The sprocket system

EXPERIMENTAL DESIGN

The motor speed controller has a dial reading with ten speed settings. Those appear as numbers (one to ten) on the dial scale. To achieve a good cross-sectional representation of the straw feeder flow rate range, four different speed settings were chosen: one, four, seven, and ten (7, 24, 42, 54 rpm, respectively). To study the effect of various agitation speeds on the straw output, the upper and lower agitator drive sprockets were changed. A combination of two number 40 sprockets having 30 and 50 teeth were used. This provided four combinations and a range of speed ratio (auger to agitator) of 1/3 to 1/5 for the lower agitator and 1/9 to 1/25 for the upper agitator as shown in Table 1. The agitators speeds in relation to the auger speed are also shown in Table 2.

A minimum of five 4 ply plastic bags (400 mm x 600 mm) were filled with straw during each experimental run. The choice of five bags per replicate was based on the principle that the hopper will not be repeatedly filled and emptied during the actual feeding of the gasification system but rather maintained at 75% capacity by the continuous feeding of the chopped straw from the straw chopper. Thus, by using the five bag procedure, the effect of the weight of straw in the hopper on the settling and consolidation process was nullified. The testing procedure included 48 experimental runs which provided 240 measurements.

Table 1. Agitators Sprockets Combinations

Combination	Teeth* Lower	Teeth* Upper	Speeds** Lower	Speeds** Upper
A	30	30	1/3	1/9
B	30	50	1/3	1/15
C	50	30	1/5	1/15
D	50	50	1/5	1/25

* The sprockets and chain are number 40
** with respect to the auger speed

Table 2. Agitator Speeds in Relation to the Auger Speed

Auger Speed Dial	Auger Speed RPM	Combination	Agitator Speed Lower	Agitator Speed Higher
1	7	A	2.33	0.78
		B	2.33	0.47
		C	1.40	0.47
		D	1.40	0.28
4	24	A	8.00	2.67
		B	8.00	1.60
		C	4.80	1.60
		D	4.80	0.96
7	42	A	14.00	4.67
		B	14.00	2.80
		C	8.40	2.80
		D	8.40	1.68
10	54	A	18.00	6.00
		B	18.00	3.60
		C	10.80	3.60
		D	10.80	2.16

EXPERIMENTAL PROCEDURE

Straw Particle Size Distribution

Samples of the chopped straw were collected randomly for sieve analysis to determine the size distribution of straw particles. An electrical sieve shaker (Hoskin Scientific Limited) driven by a 0.25 hp electric motor running at 1725 rpm was used. The shaker contained six standard sieves and a bottom pan whose specifications are given in Table 3.

The sieves were arranged according to the size of their openings. The bottom pan was placed under sieve No. 6 and designated sieve No. 7. The system of sieves was placed onto the electrically operated sieve shaker. A sample of the chopped straw was weighed and put into sieve No. 1 which was then covered with the sieve lid. The shaker was operated for 30 minutes. The straw collected in each sieve was then analyzed for weight, length

and width distribution. The results of these analyses are shown in Tables 3 and 4.

Table 3. Straw Weight Distribution

Sieve Number	Mesh Number	Opening Size (mm)	Straw (%) *
1	4	4.7600	2.90
2	8	2.3800	23.39
3	14	1.4100	35.01
4	30	0.0595	26.30
5	50	0.0299	7.55
6	100	0.0149	4.05
7	bottom pan	0.0000	0.80

* percent of total weight

Table 4. Straw Length and Width Distribution

Sieve Number	Length (mm) Range	Length (mm) Average	Width (mm) Range	Width (mm) Average
1	30.0 - 59.0	42.6	3.0 - 5.0	3.8
2	10.0 - 35.0	22.5	2.0 - 3.0	2.6
3	3.0 - 19.0	13.3	1.5 - 2.0	1.7
4	2.0 - 13.0	9.0	1.0	1.0
5	1.1 - 5.0	2.0	0.2	0.2
6	0.1 - 2.0	0.5	0.1	0.1
7	dust	dust	dust	dust

Testing Protocol

For a given experimental run (auger/agitators speed combination) the hopper was first filled with chopped straw up to a 50 mm mark below the top of the hopper. The indicator dial on the speed controller was placed on the desired speed setting. The motor was then turned on and the auger speed was fine tuned to the desired RPM (measured using a hand tachometer) by adjusting the dial controller. A small amount of straw was discharged out of the auger tube while adjusting the speed. The motor was then turned off.

The first bag was placed over the open end of the auger and the motor and stopwatch were turned on simultaneously. When the time allocated for the first bag was over, the first bag was removed and the second bag was placed over the opening. This was done carefully to avoid spilling of straw. The bag changing procedure was repeated until the fifth bag was filled. The motor was then turned off and the bags were weighed.

The hopper was refilled to the same mark. The speed setting was then changed to the next lowest test setting and the above procedure was repeated. Once the four speed settings were repeated three times each, the sprockets and chains were rearranged to provide the next auger/agitators speed combination and the same testing protocol was followed until the four speed settings on the controller dial were tried.

RESULTS AND DISCUSSIONS

Four auger speeds were used in the evaluation of the straw feeding system. These were 7, 24, 42 and 54 rpm, respectively. For each auger speed, four auger/agitators speed combinations were investigated. Three replicates were carried out for each combination and five straw bags were used for flow rate determinations. This resulted in 15 data points for each auger/agitators speed combination (or 60 data points for each auger speed).

For each auger/agitators speed combination the mean, standard deviation and coefficient of variation were calculated as shown in Table 5. The results indicated that the feeding system was capable of providing consistent straw output during each experimental run. However, both the auger speed and the agitators speed seemed to affect the straw output as illustrated in Figure 11.

Table 5. Straw Output (kg/min)

Auger Speed (rpm)	Sprocket Combination	Straw Output Mean (kg/min	Straw Output ST (kg/min)	Straw Output CV (%)
7	A	0.664	0.073	0.5
	B	0.738	0.071	0.5
	C	0.519	0.019	0.1
	D	0.660	0.073	0.5
24	A	2.311	0.111	1.2
	B	2.397	0.057	0.3
	C	2.368	0.144	2.1
	D	2.111	0.259	6.7
42	A	3.300	0.127	1.6
	B	4.237	0.196	3.8
	C	4.220	0.212	4.5
	D	3.613	0.171	2.9
54	A	3.320	0.360	11.4
	B	5.764	0.208	4.3
	C	6.749	0.273	7.5
	D	4.616	0.239	8.8

ST = standard deviation
CV = coefficient of variation

The results showed that, for a given sprockets combination, increasing the auger speed increased the straw feed rate. Also, for a given auger/lower agitator speed combination, increasing the upper agitator speed reduced the straw output.

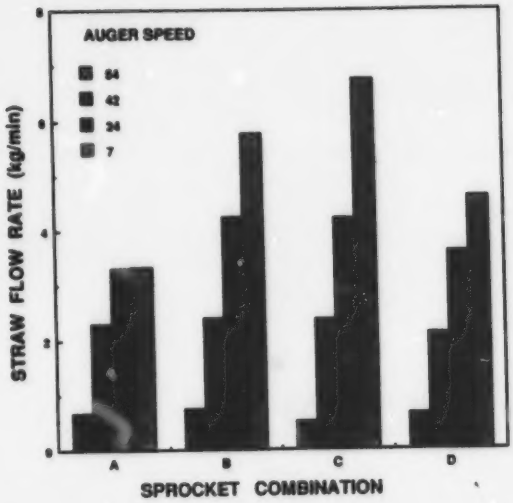

Figure 11. Straw output

This is possibly due to the mixing effect created by the upper agitator which reduced the down flow of the straw and, therefore, reduced its movement toward the auger housing.

During the testing of sprocket combination A (lowest auger/agitator speed ratio), it was observed that considerable " bridging " resulted from the high speed, of the upper agitator. The phenomena of bridging occurred when a void space was formed by the upper stratum of straw remaining intact while the lower strata were removed by the lower agitator and auger. The bridging caused the auger to operate at a level less than full capacity.

SUMMARY AND CONCLUSIONS

The evaluation of the straw feeder was set up to determine which sprocket combination yields the greatest range of straw output and to investigate the consistency of material flow. Mass flow tests were performed with four different sprocket combinations and four different auger speeds. Increasing the auger speed and/or the lower agitator speed increased the straw output of the feeding system. However, increases in the upper agitator speed resulted in reduced mass flow of the material due to the mixing effect created by the upper agitator which reduced the down movement of the straw toward the auger housing.

The sprocket C combination of a 50 tooth sprocket on the lower agitator shaft and a 30 tooth sprocket on the upper agitator shaft (lower agitator speed = 1/5 auger speed; upper agitator speed = 1/15 auger speed) gave the greatest straw output. The feed rate at this combination ranged from 0.52 to 6.75 kg/minute (8.84 to 114.75 GJ/minute), depending on the auger speed. Using sprocket combination C and by adjusting the dial controller, the output could be easily matched with the gasifier's required straw input.

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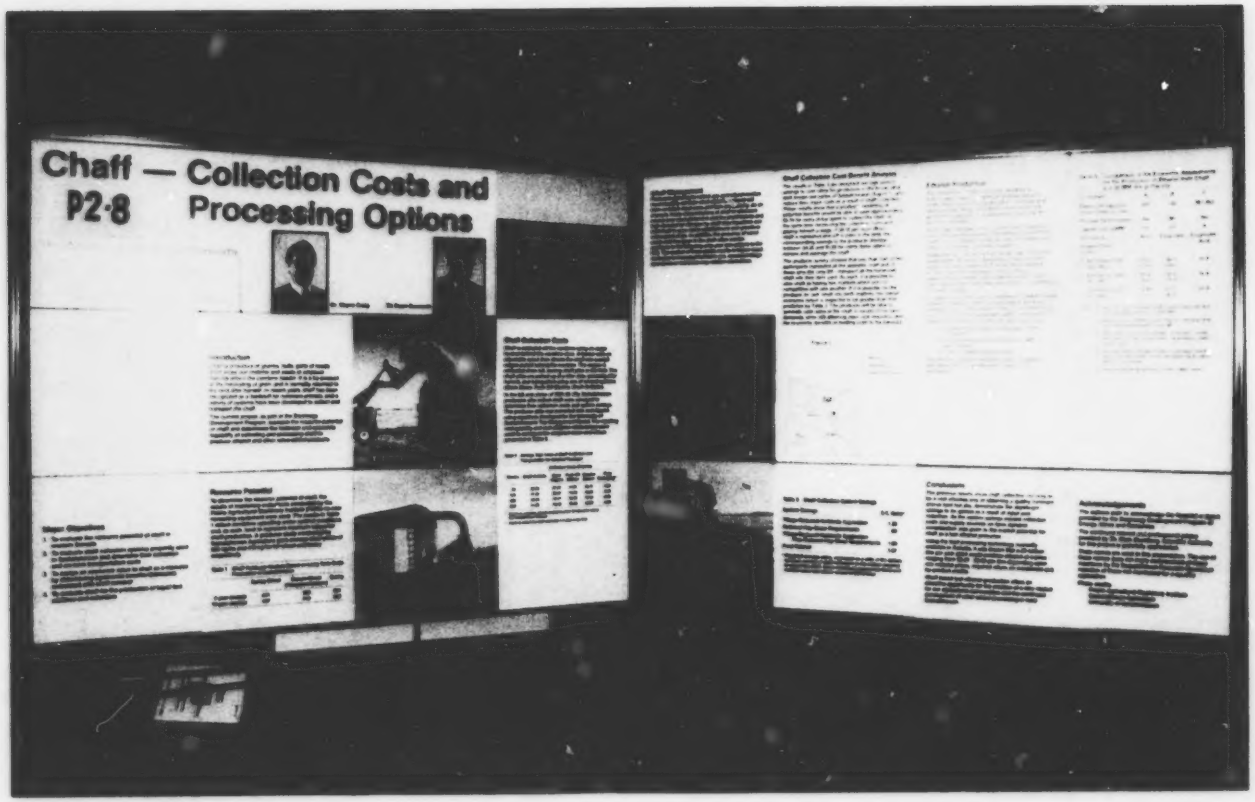

Chaff — Collection Costs and
P2-8 Processing Options

CHAFF - COLLECTION COSTS AND PROCESSING OPTIONS

W. Craig, E. Coxworth
Saskatchewan Research Council
Saskatoon, Saskatchewan

The technical and economic feasibility of collecting cereal chaff for the production of fuel ethanol is presented. The chaff resource potential in Saskatchewan was determined using PAMI historical data. A cost benefit analysis for the chaff packaging, collection and transportation systems presently used by Western Canadian farmers was conducted. The results show that regardless of the type of collection system utilized, the agronomic benefits outweigh the cost of collection both in the short and long term. Fermentation research using the best pretreatment technology currently available for lignocellulosics shows that chaff can be converted to ethanol in a similar fashion as wood residues, the yield of ethanol from chaff being the same as that from wood.

On examine la faisabilité technique et la rentabilité de la récupération de la menue paille de céréale en vue de produire de l'éthanol destiné à servir de carburant. Les ressources potentielles en menue paille de la Saskatchewan ont été déterminées à l'aide de données historiques du PAMI. On a effectué une analyse coûts-avantages des systèmes d'emballage, de récupération et de transport de la menue paille actuellement utilisés par les fermiers de l'ouest canadian. Les résultats révèlent que les avantages agronomiques dépassent de beaucoup les coûts à court et à long terme de la récupération et ce, quel que soit le type de systéme de récupération utilisé. Les recherches en fermentation faisant appel aux meilleures techniques de prétraitement actuellement disponibles pour les matières lignocellulosiques montrent que la menue paille peut, tout comme les résidus de bois, servir à fabriquer de l'éthanol avec un rendement égal.

Cette séance d'affichage peut être incluse dans n'importe lequel des domaines suivants:
- manutention et préparation de la biomasse
- production de'éthanol
- production de produits chimiques industriels
- impacts environnementaux de la production et de l'utilisation de bioénergie.

INTRODUCTION

Low commodity prices in the agricultural sector since the mid 1980's have focussed attention on a wide array of alternative crops and markets, as well as on more efficient ways of producing and utilizing existing products. This general trend, together with technological improvements in collection and processing has renewed interest in the use of chaff as both a livestock feed and as an industrial raw material.

Chaff is the residue from harvested grain crops which passes over the combine shoe and falls to the ground directly behind the combine. This material consists of glumes, hulls, parts of heads, short straw, leaf material and seeds of whatever material enters the combine header.

In the fall and winter of 1987-88, fifty randomly selected Saskatchewan producers who collect chaff were surveyed to determine costs and system savings as a result of chaff collection. The objectives of this study were to determine:

1. the raw material cost of chaff as an industrial raw material;
2. the cost/benefit relationship associated with chaff collection;
3. the technical and economic feasibility of producing fuel ethanol from chaff using the best lignocellulose to ethanol technology currently available.

RESOURCE POTENTIAL

To ascertain the resource potential of chaff, the results of the machinery evaluations conducted by the Prairie Agricultural Machinery Institute (PAMI) on new harvesting equipment were used.

The results presented in Table 1 are the chaff yields per hectare based on five and ten year averages for grain production in Saskatchewan. These results reflect combines operating under optimal conditions and, as such, tend to represent minimum values for chaff production. A producer study conducted by Saskatchewan Agriculture gave average productions of 590 kg/ha and 410 kg/ha for wheat and barley respectively.

CHAFF COLLECTION COSTS

In this study, collection costs were determined from data obtained in the survey of fifty randomly selected Saskatchewan producers. Specific information was gathered for each machine involved in the packaging (harvesting), collection and transportation of the chaff. The producer data was converted into cost figures using equations developed for the University of Saskatchewan's Top Management Model. Variable cost components measured were fuel, repairs, lubricants and labour for each machine in each system. Fixed costs were computed for all machines used primarily for chaff collection, excluding power units. For the power units, it was assumed that their involvement in chaff collection was small and as such did not significantly affect their "life". Fixed costs included the allocated costs of ownership and financial leases. The ownership costs were based on a capital recovery charge (CRC) which analyzed the investment requirement net of resale value. As much of the chaff collection equipment was either used or custom built by the producer, two different methods were used to estimate the CRC:

1. CRC based on new replacement values. This tends to overestimate the true CRC as many of the machines would never be replaced;
2. estimation of the CRC where the annual depreciation and an interest charge are based on the current "as is" fair market value.

Table 1. Saskatchewan Cereal Chaff Yields per Hectare

	Spring Wheat	Barley
	(kilograms/hectare)	
5 year average	441	251
10 year average	447	249

CHAFF COLLECTION SYSTEMS

Chaff has a much smaller particle size than straw so that the packaging, collection and transportation methods are very different. In a typical harvesting system, the chaff is collected off the combine using an auger, located behind the combine shoe, and blower assembly which blows the chaff into a small trailing wagon (Figure 1). The wagon is unloaded when full, leaving chaff piles in the field. The piles of chaff are then picked up and transported, generally after completion of the harvest, using a variety of systems:

a) Chaff-O-Matic (Figure 2)
b) Stack Wagon (Figure 3)
c) Push Off Stacker/Front End Loader (Figure 4)

Figure 1 - Chaff Wagon

Figure 2 - Chaff-O-Matic

Figure 3 - Stack Wagon

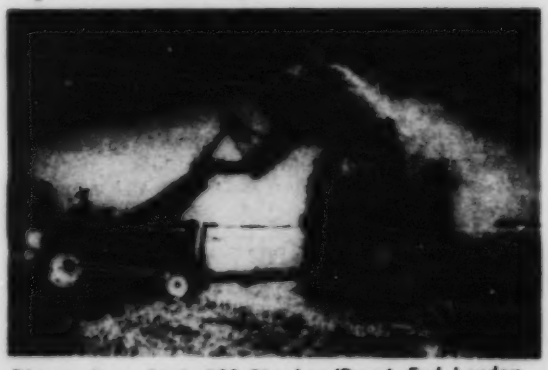


Figure 4 - Push Off Stacker/Front End Loader

Table 2. Average Total Costs of Chaff Collection and Transportation for Selected Tonnages.*

	Collection Cost ($/tonne)				
Tonnes	Chaff-O-Matic	Stack Wagons	Push Off Stacker	Vacuum Blower	Field Packaging**
50	24.29	27.67	11.81	15.17	4.04
100	17.37	22.57	11.04	13.96	4.04
300	12.76	19.17	10.53	13.16	4.04
500	11.83	18.49	10.43	13.00	4.04

*Based on producer valued equipment and a 3.2 kilometre round trip transportation distance.
** Costs to collect the chaff and leave it in piles in the field.

Transportation distance is a particularly important variable because if influences the size of the "local" market for chaff. To further examine the impact of size and transport distance, cost-quantity and cost-distance relationships were derived from the collection costs and used to construct weighted mean cost values.

Economies of size depend upon the relative magnitude of fixed to variable costs. By varying the amount of chaff collected, the impact of size on collection costs was determined (Table 2). In the case of the capital intensive systems (i.e., Chaff-O-Matic, Stack Wagon), most economies of size are reached by 200 tonnes. The other two systems are labour intensive and thus, most of the benefits of economies of size are captured quickly and costs decline relatively little beyond 50 tonnes.

COST BENEFIT ANALYSIS

Producers planning to collect any agricultural residue must carefully consider what effect its removal will have on future input costs and productivity. Conversely, the effective management of crop residues left on the land is equally important. As an example, heavy concentrations of chaff in windrows causes poor seed placement and the phytotoxicity and high demand for nitrogen by chaff decomposition can contribute to poor stand establishment and growth in subsequent crops. In addition, the presence of weed seeds and free grain in the chaff often creates problems in the following crop year. The control of these plants results in higher input costs due to increased herbicide use, increased tillage operations or restricted crop rotation alternatives.

As part of our survey, participants were asked to describe and, wherever possible,quantitate system benefits directly attributable to chaff collection. The dollar value of these system savings were then calculated in an identical manner as previously described for the chaff collection costs.

The results in Table 3 are the system savings to cost ratios (s/c) for the producers in the brown and dark brown soil zones of Saskatchewan who observe agronomic benefits. The s/c ratios are weighted averages taking into account each farm's s/c ratio and the number of tonnes of chaff collected.

The s/c ratios for tillage and herbicide reduction were calculated considering the direct chemical savings and the variable, fixed and labour costs associated with either a single tillage operation or the spray application of herbicides.

The reduced hay/straw requirement s/c ratio was calculated by considering a producer's feed/bedding requirement prior to and after chaff collection had been implemented. In this case, the savings result from less hay having to be cut and less hay and straw having to be baled, collected and transported to the farm yard.

The feed related s/c ratio for chaff was calculated by subtracting each farm's collection costs from the proxy value of chaff. The proxy value was determined by multiplying the number of tonnes of chaff collected by the economic value of chaff ($35.56/tonne) as quoted in the June 1988 edition of Saskatchewan Agricultures' Feed Testing Service bulletin. This latter value was calculated by comparing the average nutritive value of chaff samples analyzed by the Saskatchewan Feed Testing Lab (crude protein, TDN, minerals, etc.) with other reference feeds.

The results in Table 3 show that a producer obtaining all potential savings would be able to save approximately $2.76 for every dollar spent to collect the chaff at the same time recovering his collection costs and paying himself a wage of $8.50 per hour.

For the situation where all packaged chaff would be moved off-farm, the producer could only expect to gain the agronomic and not the feed

related benefits. In this case, the chaff collection costs would be restricted to the chaff packaging costs, i.e., the fixed and variable costs to place the chaff in piles in the field. Based on our producer survey, the weighted average total cost per tonne to package chaff ranges from $4.04 (market valued equipment) to $5.66 (new equipment). The corresponding s/c ratio ranges from 4.20 to 5.79 depending on the evaluation of the producer's equipment.

Observations made during the survey show that slightly less than half of the participants package all their available wheat chaff and of those who do, only 60% moved all the packaged chaff into their farm yard.

As such, it is possible to view chaff as having two potential markets which are not competitive with one another (i.e., on-farm as a feed and off-farm as an industrial raw material). The degree to which the system benefits could be assigned to the raw material entering each market would be difficult to determine but for the producer, this scenario would offer access to all of the previously discussed benefits. Specifically, the producer could:

- increase his/her chance of obtaining the agronomic benefits;
- still gain the economic benefits of feeding chaff to his/her livestock;
- generate revenue from the cash sales of the surplus chaff thereby offsetting the chaff packaging and on-farm transportation costs.

Should it be possible for the producer to "sell" chaff into both markets, the overall economic return would be greater than that predicted by Table 3.

Table 3. Chaff Collection System Savings

System Savings	S/C Ratio*
Tillage/Reduced Herbicide Application	1.28
Reduced Hay/Straw Requirements	.69
Tillage/Reduced Herbicide Application Plus Reduced Hay/Straw Requirements	1.69
Feed Related	1.07

* Weighted average ratios, expressed as a ratio of the dollars saved as a result of chaff collection to the dollars required to collect the chaff. Costs include all appropriate fixed and variable costs and include labour valued at $8.50/hour.

ETHANOL PRODUCTION

In the past several years there has been considerable attention devoted to evaluating alternative sources of transportation fuels. Of the alternatives now available, one of the most attractive for a long term contribution is fuel ethanol. Since the cost of raw materials contributes significantly to the overall cost of producing liquid fuels, it is important that cheap, renewable agricultural and wood residues be evaluated as feedstocks. For Western Canada, which is blessed with abundant agricultural resources, an important biornergy source could be chaff.

The conversion of lignocellulosic residues to fermentable sugars is a difficult process because of the close association of the lignin, cellulose and hemicellulose. The conversion of the structural material to sugars can be accomplished by enzymatic hydrolysis but this process requires pretreating the biomass substrate. A principle objective of this project was to examine the technical and economic feasibility of converting chaff into fuel ethanol. Within this general context, the yield and the cost per litre was determined using the best technology currently available for lignocellulosic conversion. The four (pretreatment/processing) technologies evaluated include those developed by:

a) Stake Tech
b) Iogen/Techtrol
c) Dr. Morris Wayman
d) BioHol/St. Lawrence Reactors

Based on their own technical results, each consultant assessed the economic feasibility of their process using chaff as a feedstock. The results presented in Table 4 are a comparison of their economic assessments in which variables such as the size of the ethanol plant, raw material costs and return on investment are held constant.

The results of the economic assessment conducted by Iogen/Techtrol are not included in this table as their study showed that for a 15% return on investment, by-product credits of $121/tonne and $100/tonne for the hemicellulose and lignin streams respectively, a raw material cost of $10 per tonne and existing enzyme technology, a 160 million litre per year ethanol facility could produce ethanol for $0.61 per litre. If the size of the production facility were reduced to 20 million litres per year, it was Iogen's opinion that the cost of ethanol would be increased by approximately $0.40 per litre.

In terms of the geographic area and transportation radius that would be necessary to support a 20 million litre per year ethanol plant, if we assume:

1) a yield of 250 litres of ethanol/tonne of chaff;
2) a resource potential of 500 kg of chaff/hectare;
3) a 50% participation rate;

Table 4. Comparison of the Economic Assessments Conducted by St. Lawrence Reactors/ BioMol, Stake Tech and Dr. Morris Wayman for the Production of Ethanol from Chaff in a 20 million litre/yr Facility.

	SLR/BioMol	Stake Tech	Dr. M. Wayman
Ethanol Production (litres/tonne of chaff)	259	142	367-403
Pentose Fermentation	Yes	No	Yes
Capital Cost ($ MM)	$15	$53	$9
Hydrolysis	Acid	Enzymatic	Enzymatic/Acid
Ethanol Cost (¢/litre)			
a) $10.00/tonne chaff	23.3[A]	34.0[C]	N/A
20% ROI	31.6[B]	68.0[D]	
b) $15.00/tonne chaff	25.3[A]	38.0[C]	N/A
20% ROI	33.6[B]	72.0[D]	
c) $15.00/tonne chaff	32.8[A]	57.0[C]	24.0[E]
30% ROI	41.1[B]	90.0[D]	

where A assumes a by-product credit (lignin, cellulose and hemicellulose derived) of $150/MT

B assumes a by-product credit (lignin, cellulose and hemicellulose derived) of $75/MT

C assumes hemicellulose stream by-product credit (furfural) of $1.95/kg and lignin by-product credit of $88/tonne.

D assumes hemicellulose stream by-product credit (xylose syrup) of $40/tonne and lignin by-product credit of $88/tonne

E assumes lignin by-product credit of $69/tonne

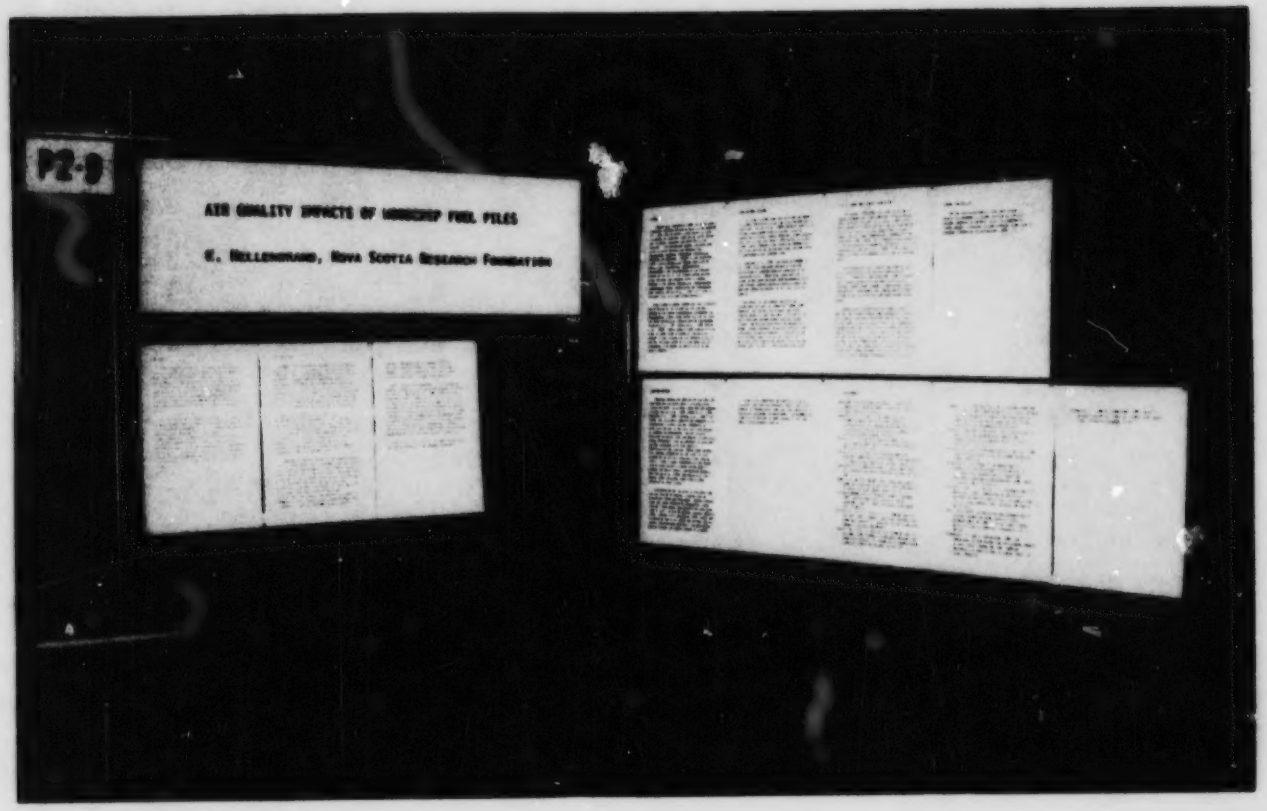
the effective collection area would be 56.2 square kilometres (35.15 square miles) with a one way maximum transportation radius of 31.7 kilometres (19.8 miles). This transportation radius is quite reasonable considering the economies of size to be gained by the ethanol plant collecting the chaff directly from the farmer's fields and the fact that several of our survey participants were hauling chaff 13.0 kilometres (8.0 miles). for their own use.

CONCLUSIONS

The previous results show chaff collection not only to be a cost effective way of obtaining a quality ruminant animal feed but also demonstrate the significant producer savings to be gained through input cost reduction. As the system savings exceed the collection costs and the supply exceeds the on-farm demand as a feedstuff, consideration was given to the market potential for chaff as a fuel ethanol precursor.

Using the best pretreatment/processing technology currently available in Canada, it was shown that a 20 million litre per year plant could produce ethanol at prices ranging from $.23-$.90 per litre depending upon raw material costs, required return on investment and by-product credits.

Consideration of the resource potential in Saskatchewan shows that wheat chaff could yield between 850 and 1400 million litres of fuel ethanol per year at the same creating a new industrial market for our agricultural commodities and the continued development of a secondary processing industry in rural Saskatchewan.


P2-9
AIR QUALITY IMPACTS OF WOODCHIP FUEL PILES
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AIR QUALITY IMPACTS OF WOODCHIP FUEL PILES

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The increasing use of woodchips as an energy source will result in an increase in the numbers of woodchip piles in domestic and institutional environments. The presence of these piles may have an adverse effect on the quality of the air around them because of fungi surviving or growing on the wood. This study is intended to assess this potential problem and recommend a protocol for monitoring air quality in the vicinity of woodchip piles.

L'utilisation de plus en plus fréquente de copeaux de bois comme source d'énergie se traduira par un accroissement du nombre de tas de copeaux de bois à proximité des résidences et des grand etablissements. La présence de ces tas peut avoir des effets néfastes sur la qualité de l'air à proximité, car il y a des champignons qui croissent sur le bois. Le but de cette étude est d'évaluer ce risque et de recommander un protocole de contrôle de la qualité de l'air à proximité des tas de copeaux de bois.

INTRODUCTION

There is an increasing interest in the use of woodchips for fuel in domestic and institutional furnaces. This is driven partly by a desire to use renewable, rather than non-renewable energy resources, and partly by concerns over the future price of fossil fuels since the high oil prices experienced in the mid 1970's. Using woodchips for fuel will open new markets for the forest industries but may also create some problems as an unfamiliar product is introduced into the indoor environment.

Woodchips stored in piles are subject to deterioration by a wide range of fungi depending on the conditions under which they are stored. In addition to mesophilic species, thermophiles occur in cases where the pile has undergone self-heating as a result of microbial growth (Hoover-Litty & Hanlin, 1985). Thermotolerant species, eg. Aspergillus fumigatus, are found in both ambient temperature and self-heated piles.

Commercial woodchip users in the pulp and paper industry have mainly been concerned over the loss of wood fibre and undesirable colour changes caused by fungi (Smith, 1972). Because large industrial chip piles are stored outdoors, the health implications of the presence of fungi has received less attention. However, when woodchips are used as a fuel source and are stored in homes and institutional buildings, the presence of large numbers of fungi, particularly thermotolerant and thermophilic species, becomes of much greater concern. Depending on the species of fungi involved, people exposed to spores, mycelial fragments, volatile products, etc. may suffer allergic reactions, toxicosis or infection.

While there is an awareness of the potential problem of the effect of woodchip storage on indoor air quality (Miller et al., 1982: Thornqvist & Lundstrom, 1982), there is, as yet, little to guide the analyst in the best ways to sample the air in a building for fungi and how to interpret the results obtained. The objective of this project is to draw together existing information on determining fungi in indoor air in relation to the potential hazards posed by indoor woodchip storage and to produce a protocol for the systematic monitoring of buildings where woodchip heating and storage is practised.

This project is still in its early stages hence the present report is preliminary in nature.

FUNGI

Hoover-Litty and Hanlin (1985) in their study of woodchips intended for use as mulch in the southern U.S. note that although a wide variety of fungi colonized the woodchips (114 species in 82 genera), only 6 genera accounted for about 49% of the isolates. The predominant genera, isolated from piles of mixed softwood and hardwood were Trichoderma, Fusarium, Chaetomium, Aspergillus, Rhizopus and Graphium. Thornqvist and Lundstrom (1982) listed Aspergillus, Mucor, Paecilomyces, Penicillium, Talaromyces, Phanerochaete and Chrysosporium as the dominant genera in the air of chip storage rooms holding mixed softwood and hardwood chips in Sweden. Members of the genera Aspergillus, Aureobasidium, Cladosporium, Mucor, Penicillium and Trichoderma were found by Miller et al., (1982) in a study of softwood chips in a home in New Brunswick.

Fungi found in normal indoor air tend to reflect the mycoflora of the outside air and are mostly members of the genera Cladosporium, Alternaria and Aureobasidium. Many other genera can also be found including Aspergillus, Penicillium and Trichoderma (Fradkin et al., 1987: Kozack et al., 1980; Hunter et al., 1988). While there is some overlap with the kinds of fungi found on woodchips the relative numbers of each species will be important clues to whether the fungi found in a given sample may be considered to be normal or indicative of an air quality problem.

HEALTH IMPLICATIONS

It is well established that exposure of humans to fungal propagules in air can cause adverse health reactions. Kozack et al. (1980) reported surveys of several homes where cases of allergy could be associated with mold growth problems. These authors note that allergy may result from contact with non-viable fungal fragments and spores an observation which has bearing on the methods used for monitoring of environments for airborne fungi.

Jappinen et al. (1987) and Kolmodin-Hedman et al. (1987) have published reports of problems encountered by workers handling woodchips on an industrial scale. Where high concentrations of fungal spores were released from biodegraded chips some exposed workers exhibited feverish reactions and some showed antibodies to the fungi in blood samples.

The report of the working group on the significance of fungi in indoor air (Anon, 1987) indicates that as well as allergic reactions, inhaled spores of fungi may result in direct lung infections and further fungal invasion of body tissues. Mycotoxins which might be present in spores, hyphal fragments or on dust particles may also result in health problems. Exposure of the skin to fungal particles may only result in relatively minor irritation unless mycotoxins are present when the reaction may be much more severe.

TYPE OF WOOD AND STORAGE CONDITIONS

In general, softwoods are more resistant to fungal degradation than hardwoods (Kirk & Moore, 1972) but this may not be of great significance where relatively minor destruction of wood matter could still result in the production of large quantities of fungal propagules. Thornqvist and Lundstrom (1982) found that airborne fungi increased as the proportion of hardwoods in indoor chip piles increased but Miller et al. (1982) found lower counts of fungi on hardwood chips than on softwood chips.

The methods of chip storage and handling will have a major effect on their microbiological quality. Thornqvist and Lundstrom (1982) suggest that storage after chipping should be limited although longer term storage of nonchipped wood is permissible. Presumably the larger surface area exposed after chipping will encourage more fungal growth.

Large piles of woodchips are prone to self-heating and thermotolerant and thermophilic fungi will tend to dominate the mycoflora in the inner, hotter zones. Some of these fungi, eg. Aspergillus fumigatus are implicated in health problems ranging from allergenicity to direct infection and others must be viewed with caution because of their ability to grow at body temperature. Ventilation may be used to limit the temperature in woodchip piles but if the chips have suffered previous heating this may actually cause further dissemination of existing fungal propagules.

Drying woodchips rapidly has been shown to reduce the numbers of fungal propagules initially present whereas in undried chips the numbers of viable spores increased several hundred times during storage (Thornqvist & Gustafsson, 1983).

SAMPLING METHODS

Numerous methods for sampling air for fungi have been employed including gravity settling plates, liquid impingers, solid media impactors and membrane filters (Kozack et al., 1980; Lembke et al., 1981; Palmgren et al., 1986; Placenia et al., 1982). Of these, the solid media impactor and membrane filter methods seem to offer the best compromise of simplicity for use in the field with good recovery of airborne microorganisms. As some allergic reactions may result from the presence of non-viable fungal propagules it may be necessary to supplement culture techniques with total particle identification and counting. While these methods will provide information on the effect of chip storage on the air in a building it may also be useful to make a direct assessment of the fungal load of chips prior to storage in the home to prevent the use of heavily contaminated material. Both Miller et al. (1982) and Hoover-Litty and Hanlin (1985) recovered fungi directly from woodchips in their studies.

Consideration must be given to the media used for cultivation of samples to ensure that no significant fungi are overlooked. Rapidly growing fungi may cause problems by overgrowing slower species. Rose bengal and Triton N-101 have been used to limit the faster growing isolates (Madelin, 1987). Hoover-Litty and Hanlin (1985) found that although no one of six media was optimal for all genera isolated from woodchips, the rose bengal medium yielded the largest number of colonies.

Finally the importance of identification of isolated fungi must be stressed. While very high numbers of unidentified fungi per cubic metre may a priori be considered as undesirable, low numbers may constitute a similar or worse hazard if they are made up of pathogenic species.

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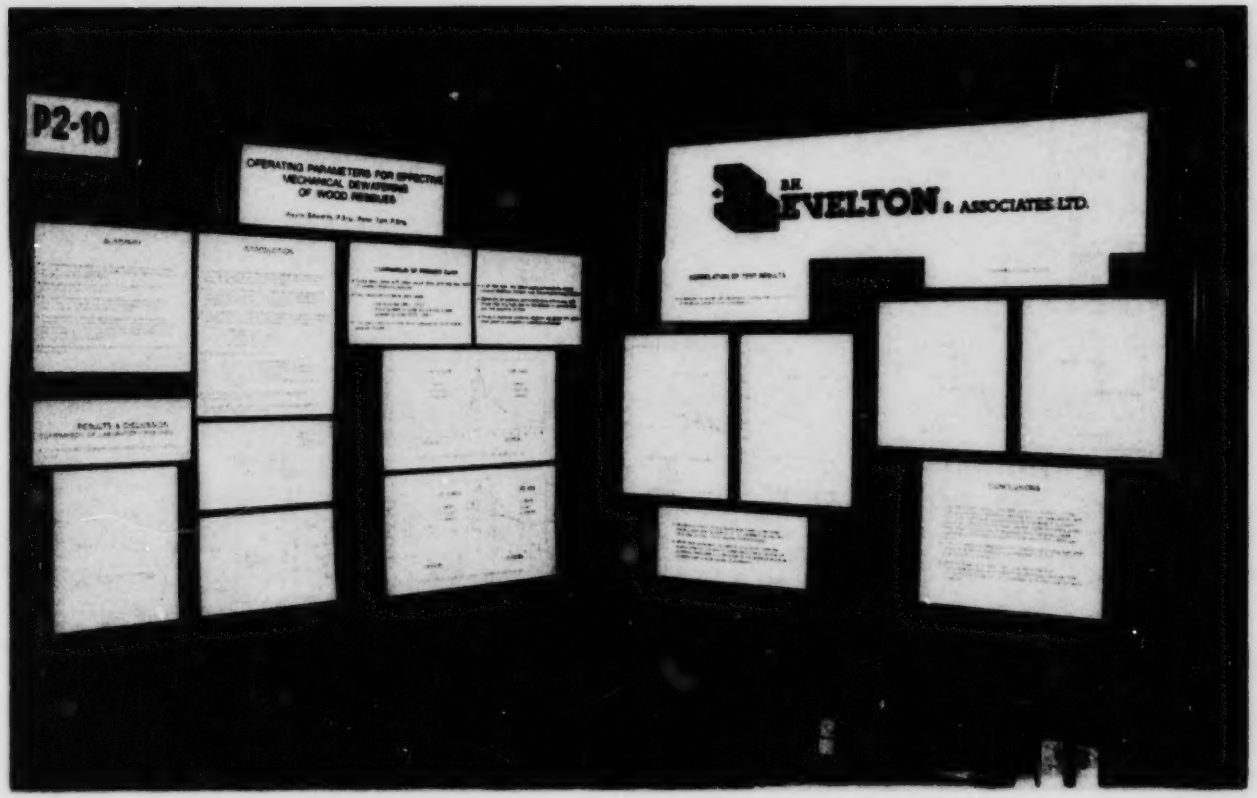
P2-10
OPERATING PARAMETERS FOR EFFECTIVE MECHANICAL DEWATERING OF WOOD RESIDUES
B.H. EVELTON & ASSOCIATES LTD.

OPERATING PARAMETERS FOR EFFECTIVE MECHANICAL DEWATERING OF WOOD RESIDUES

Wayne Edwards, P.Eng., Peter Tam, P.Eng.

B.H. Levelton & Associates Ltd.
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Commercially available dewatering presses for wood residues reduce moisture content to 50 - 55%, wet basis under normal operating conditions, and to as low as 45%, wet basis under very good conditions and when the equipment is well maintained and operated. Improvements to the design of dewatering presses for wood residues are desirable since lowering of the moisture content below levels currently reached would significantly improve the efficiency and stability of combustion.

A comprehensive test program was completed with three laboratory scale presses: a platen press; a ram press; and an extrusion roller press. Tests were done with clean wood chips and with hogged residues of Western hemlock species at the moisture content as-received from a local sawmill, and after soaking in water for 24 hours and draining. Other important feed properties were measured and documented.

For both feedstocks, the platen press was the most effective for dewatering, requiring the least pressure to reach a given product moisture content. The second most effective design for wood chips was the roll press.

Les presses essoreuses disponibles dans le commerce permettent de reduire jusqu'a 50 - 55% (poids humide) la teneur en humidite des residus de bois dans des conditions normales de fonctionnement, et jusqu'a 45% (poids humide) lorsque les conditions sont tres bonnes et que le materiel est entretenu et utilise de facon appropriee. Il serait souhaitable d'ameliorer la conception des presses servant a l'essorage des residus de bois, car toute dimunition de la teneur en humidite a une valeur inferieure aux teneurs actuellement atteintes permettrait d'ameliorer considerablement l'efficacite et la stabilite de la combustion.

Un programme de'essais exhaustifs a ete realise avec trois presses de laboratoire, soit une presse a plateau, une presse a piston et une presse a cylindre. Les essais ont ete effectues avec des copeaux de bois propres et avec des dechets de bois de pruche de l'Ouest, a une teneur en humidite correspondant a la teneur apres reception de la scierie locale et apres immersion dans de l'eau 24 heures et egouttage. On a mesure et documente d'autres importantes proprietes de la charge d'alimentation.

Pour les deux charges d'alimentation, la presse a plateau etait la plus efficace en ce qui concerne l'essorage, la pression necessaire pour obtenir une teneur en humidite donnee etant la plus faible dans ce cas. Dans le cas des copeaux de bois, c'est la presse a extrusion qui se classait au second rang.

INTRODUCTION

Mechanical dewatering equipment is used widely in the forest products industry for reducing the moisture content of wood residue fuels. A prime candidate for mechanical dewatering is bark discharged from hydraulic debarkers, since its moisture content is typically in excess of 65%, wb. Many other residue streams in forest products mills have moisture contents in excess of 55%, wb. For all of these wet fuels, reduction of the moisture content is certainly beneficial and often essential before they can be burned efficiently and without combustion instability problems. Currently used mechanical dewatering equipment is capable on a routine basis of reducing the moisture content of wood residues to 50 - 55%. Under very good conditions, product moisture contents can reach as low as 45%, but this is generally not the norm.

Mechanical dewatering presses have a lower capital cost than thermal drying systems for wet residues, but need routine maintenance and adjustment to keep them operating effectively.

The cost of maintenance and the need for routine operating adjustments are frequent complaints from industrial users. Thermal systems must be used to reduce moisture contents to 45%, wb, or below, since mechanical dewatering presses now available commercially are not capable of reaching these levels on a sustained basis.

When comparing mechanical and thermal methods of removing water from wood residues, the mechanical dewatering process has several advantages: no thermal energy is needed; less space is required; no emissions of air pollutants occur; and the capital cost is lower. The main disadvantage of mechanical dewatering is that the product moisture content typically cannot be reduced below 50%, wb. Another consideration is that proper treatment of the effluent from dewatering presses is needed before it can be discharged to the environment because of the suspended solids and extractives that are present.

Very little study of the fundamentals of dewatering of wood residues, such as hogged wood and bark, has been reported in the published literature. Undoubtedly, the dewatering presses for wood residues currently marketed have been extensively tested, but this data is not publically available.

A study (Edwards and Tam, 1988) was undertaken to address the lack of fundamental understanding of dewatering of wood residues and the need for more information on the type and performance of equipment currently used. Data on the operation of dewatering presses was obtained from suppliers and equipment users. Tests were done at a laboratory scale to investigate three generic press configurations: platen press; ram press; and roller press. These designs are now used in one form or another in commercial dewatering presses. The laboratory results were correlated using a simple dewatering model, providing a valuable tool for predicting the effects of different operating conditions and material properties. The results of the study were used to recommend means of improving existing presses and develop a new conceptual design.

RESULTS AND DISCUSSION

Commercial Presses

Various designs of equipment are available commercially for dewatering of wood and bark residues. Equipment suppliers by type of press used in the design are:

Roll Press	- Fulton Iron Works Co.
Chain Press	- FMP-Rauma
Roll/Perforated Drum Press	- Saalasti Oy
	- Enso-Gutzeit Oy
Ram Press	- S.W. Hooper and Co. Ltd.

Table 1 summarizes the specifications and typical performance under preferred conditions for proven dewatering equipment for wood and bark residues.

Fulton Iron Works Co. manufactures a roll press for dewatering of hogged wood and bark, bark and sludge mixtures, and other bulk materials. The press uses three grooved rolls arranged with two at the bottom and one at the top. Feed enters a hopper from the top and is drawn between the upper roll and the feed roll resulting in some water removal. The produced mat passes across a bridge plate from the nip of the feed roll to the nip of the discharge roll. The mat is further compressed in the nip of the discharge roll, removing more water, and is then discharged from the press. Most water is removed when the mat is compressed in the nip of the discharge roll. The effective pressure in this area when processing hogged residues is about 17.2 MPa. Material is exposed to high pressure for 2 - 3 seconds. The pressure on the lower rolls from the single upper roll is maintained by adjustable hydraulic pressure, which can be set to a desired level.

FMP-Rauma now markets the FMP bark press previously available from Horton CBI, Ltd. This is a chain press which utilizes the pressure developed by the chain on an unpowered roll to dewater wood and bark residues. Wet feed enters the press at the top and is pressed between the chain and the roll before discharge. Pressure on the material is produced by the action of three hydraulically actuated outer rollers and increases as material passes through the press.

The roll press made by Saalasti Oy and sold under the name Bark Master dewaters bark and wood residues using pressure developed between an inner powered roller and an outer unpowered perforated drum. Material is fed to the upper end of the press between the roller and the drum by a feed screw. Expressed water drains out through conically drilled holes in the drum designed to prevent plugging. The drum and inner roller are at a 10° - 15° decline causing the wet feed to tumble forward along the drum and to be pressed 4 - 5 times before being discharged. The material typically remains in the press for 2 - 3 minutes and is in the nip between the drum and the roller for about one minute.

Information was obtained on the operating performance of Bark Master presses installed at the Port Alice and Squamish mills of Western Pulp Partnership Ltd. Two Model 83 units are used at Port Alice, while one is used at Squamish. The press at Squamish has performed well, yielding an output moisture content of nearly 50% for bark feed from a hydraulic debarker (70% moisture content). The Port Alice mill has two Bark Master 83 Model 2 presses for dewatering bark from the hydraulic debarker. The units reduce feed moisture from 67 - 72% to 55% on average.

Table 1 Typical Performance of Mechanical Dewatering Equipment

Equipment Description				
Ram Press	Drum Press	Drum Press	Roll Press	Chain Press
S.W. Hooper and and Co. Ltd.	Saalasti-Oy	Enso-Gutzeit Oy	Fulton Iron Works Co.	FMP-Rauma Ltd.
Best Application				
Minimum capital cost. Can tolerate tolerate intermittent fuel feed, hogged or feed, hogged or unhogged.	Continuous process. Very wet material. Hogged or unhogged bark.	Continuous process. Wet bark. Hogged and suitably sized for screw conveying.	Continuous process. Very wet fuel. Hogged clean bark.	Continuous process. Hogged or unhogged fuel.
Fuel Size				
Any size that can enter the hopper but large pieces will reduce dewatering efficiency	Occasional piece: 200 x 200 x 600mm	Occasional piece: Model 1400 x 500 Size 25 x 75 x 250mm Model 1700 x 750 Size 50 x 100 x 305mm	100 x 100 x 100mm	100 x 100 x 100mm occasional piece 100mm dia x 1.2 m
Sensitivity to Rocks/Metal				
Low: Hydraulic overload protection prevents damage	Low: Rocks smaller than 200 x 200 x 200mm or metal smaller than 500mm dia x 600 mm lg or similar size can be processed without damage.	Medium: Model 1700 x 750 Rocks 0-100 mm dia Metal 0-50 mm dia	Very high: 25 x 25 x 25mm or smaller will pass without damage.	Medium: 100 x 100 x 100mm or smaller will pass without damage.
Capacities				
5.5 dry t/h	8-11 dry t/h	2.2-3.8 dry t/h	1.4-6.3 dry t/h	6.8-11.3 dry t/h
Minimum Fuel Moisture				
45%	55%	45%	45%	50% - Varies with size and initial fuel MC
Maintenance Costs				
$ 0.33/dry t	$ 0.22/dry t	$ 0.28/dry t	$ 0.77/dry t	$ 0.55/dry t

Costs for maintenance have been estimated by mill personnel for each unit to be:

- $ 60,500 every 2 years for repairs to drums, roll, shafts, etc. (labour and material);
- $ 3,000/yr for cleaning drum holes;
- $ 500/yr for alignment of roller

Enso Gutzeit Oy manufactures a roller press for dewatering wood and bark on a continuous basis. Wet feed is distributed evenly across the face of the roll by a screw conveyor. The powered drum draws the wet material between itself and the inner roller, exposing the material to a high pressure. Expressed water passes out through holes in the drum. The roller and drum are designed so that the material is under pressure for about 90° of rotation. After leaving the roller nip, the material remains on the inner surface of the drum until it is scraped free and falls onto an outfeed screw conveyor. The drum is rotated in increments by the action of a ratchet drive, while the inner roller is unpowered and rotated by the frictional force developed by the material under pressure. The speed of the drum is controlled by varying the

rate of movement of the hydraulic cylinder used to drive the ratchet.

An Enso press has recently been installed at MacMillan Bloedel's mill in Port Alberni. Results are not yet available on the performance of the press.

The Hooper press can be used to dewater wood and/or bark either hogged or unhogged at a rate of up to 28 m^3/h (loose). The press uses a reciprocating ram and pressing beam to dewater material cyclically on a batch basis. The capacity of the unit on a weight basis depends on the density of the feed.

Theory of Dewatering

A model has been developed for dewatering of solid wood by mechanical compression (Haygreen, 1981). Wingate-Hill (1985) conducted experimental tests of mechanical compression drying and attempted to utilize Haygreen's model to correlate the results.

Using volume and mass balances Haygreen developed the basic equation for moisture content as a function of compression, and a saturation factor to be:

$$MC = X + S\left[\frac{(1-C)}{SG_i} - \frac{\rho}{\rho_{drywood}} - \frac{X\rho}{\rho_{boundwater}}\right] \qquad (1)$$

where,

- MC = moisture content of compressed wood on a dry basis
- X = fraction by weight of water present in wood substance at fibre saturation
- S = degree of saturation of cell voids with water, expressed as a fraction
- C = volumetric compression
  = (Initial volume - Compressed volume)/Initial volume
- SG_i = initial specific gravity of wood based on dry wood mass and total wet volume
- ρ = density of water
- $\rho_{bound\ water}$ = density of water in the wood substance
- $\rho_{dry\ wood}$ = density of dry wood substance based on wet volume

In his analysis of dewatering of solid wood by compression Haygreen (1981) and later, Wingate-Hill (1985) assume S remained constant during compression. This is equivalent to the volume of air and water staying in the same proportion during dewatering as it originally existed. With this assumption, moisture content becomes a linear function of compressibility, C.

In this work and that of Wingate-Hill (1985), saturation, S, has been found to vary substantially during compression and the simplified equation for moisture content as function of compression, consequently, is poor for correlating dewatering behavior.

By inspection of experimental results from dewatering of hog fuel and chips in a platen press it was hypothesized that the product S(1-C) remains approximately constant during compression. With this assumption, equation (1) reduces to:

$$MC = MC_i - kS^* \left(\frac{C}{1-C}\right) \qquad (2)$$

where,

- MC_i = initial moisture content on a dry basis
- MC = moisture content of compressed wood on a dry basis
- S* = constant
- C = volumetric compression expressed as a fraction
- $k = \frac{\rho}{\rho_{dry\ wood}} + \frac{X\rho}{\rho_{bound\ water}}$

A plot of moisture content on a dry basis versus C/1-C should be a straight line with a slope of -kS* and a y-intercept of the initial moisture content. Equation (2) was used to correlate the results of tests under various conditions with the platen press.

Comparison of Laboratory Presses

Laboratory scale tests were done with a platen press (184.2 mm diameter), a ram press (59 mm diameter) and a roller press with ram feeder (opposed rollers 219.1 mm diameter by 57.2 mm wide). All presses were driven hydraulically.

Tests were done with clean wood chips and hog fuel, both of Western hemlock species. Feed materials were obtained from a sawmill in Vancouver. One set of tests was done with feed at an as-received moisture content, while another set was done after soaking the feed in water for 24 hours and allowing it to drain. The moisture contents differed between the two types of feed materials for both the as-received and soaked test runs. Various other properties of the feedstocks were measured.

Figure 1 shows the performance of the three presses when using as-received and soaked wood chips. For as-received chips, as in all other test runs, the platen press achieved the lowest product moisture content over the pressure range tested with the unit. Extrapolating the data for the roller press back to a similar as-received moisture content, suggests that the two presses yield similar results up to near 15 MPa, after which the roller press yields superior results. For soaked chips, the roller and ram presses yielded similar product moisture contents over the common pressure range tested.

The dewatering curves for hog fuel differ significantly from those for chips (Figure 2). As observed for chips, the platen press is the most effective press design. In the case of as-received hog fuel, the initial moisture content

was unfortunately significantly lower for the platen press than for the other two presses. However, analysis of test data shows that the effect of initial moisture content decreases rapidly with increasing pressure up to 5 -10 MPa, after which a fairly constant difference in product moisture content of 2 to 3% persisted between the soaked and as-received feedstocks, even to the maximum pressure tested. These results suggest the platen press would have achieved lower product moisture contents than those found for the other presses if the initial moisture content for as-received hog fuel had been comparable in magnitude. The product moisture contents for soaked hog fuel feedstocks were similar for all press designs at a pressure of near 20 MPa, though the platen press yielded much lower results at lower pressures.

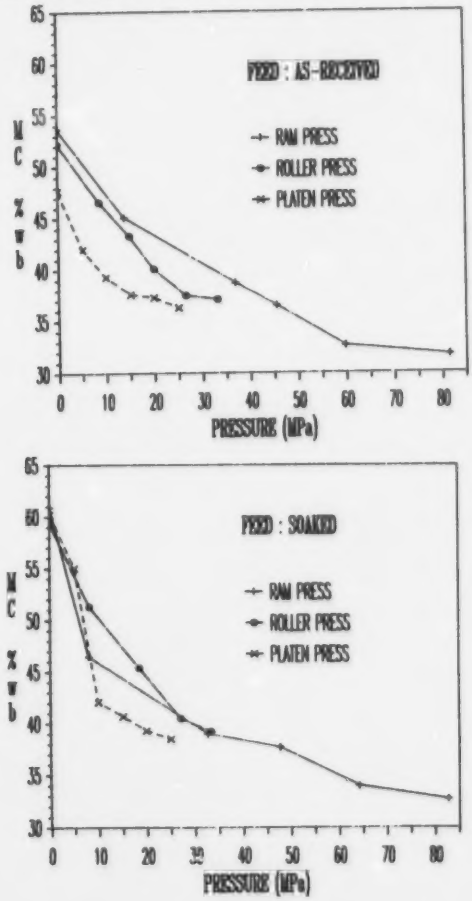

Figure 1 Comparison of Platen Press, Ram Press, and Roller Press for Hemlock Chips

Generally, all of the presses performed more effectively with chips than with hog fuel. This is attributed to the effects of particle size and the fact that no bark was present. At 25 MPa, the highest pressure tested with the platen press, product moisture contents were 36.5%, wb and 38.5% wb for as-received and soaked wood chips, respectively. Product moisture contents were somewhat higher for hog fuel in the platen press, being 37.5% and 43% for as-received and soaked cases, respectively. These moisture contents are about 10% less than what is achieved in commercial presses.

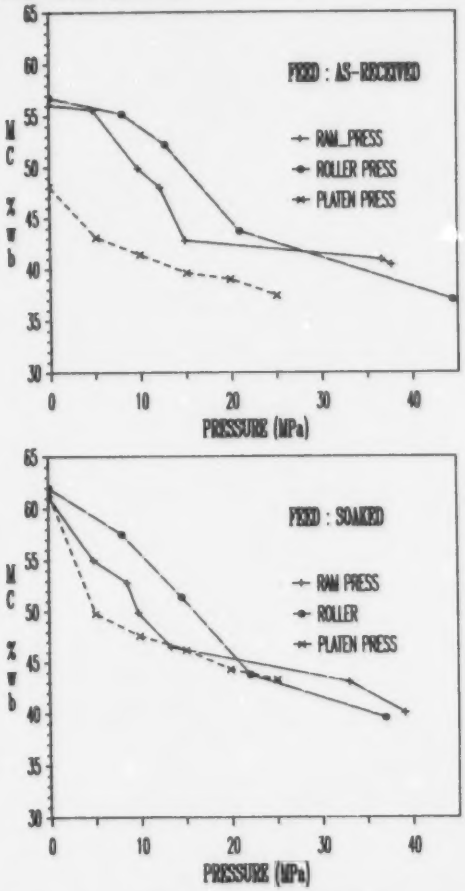

Figure 2 Comparison of Platen Press, Ram Press and Roller Press for Hemlock Hog Fuel

Correlation of Test Results

Equation (2) was used to correlate average test results obtained with the platen press using chips and hog fuel. These tests were chosen because measurements of compression as a function of pressure could be made, while this was not possible for the other two presses. Average results for tests done with residence times of 1 and 2 minutes are given in Figures 3 and 4 for wood chips and hog fuel, respectively. In spite of the fact that S(1-C) varies moderately over the range tested, the data is surprisingly linear, yielding correlation coefficients of 0.979 to 0.996 for the four cases shown. For wood chips, product moistures for the two cases of initial moisture content become equal at a compression ratio of 5.63 and a product moisture content of 54.1% db. A very similar value for product moisture content, 53.3% db, is found for

hog fuel at a compression ratio of 4.78 if the correlations for the two feedstock cases are extrapolated.

It is expected that for most practical cases, 54% db is a lower limit for product moisture content by mechanical pressing.

Correlations were developed from tests of compression of wood chips and hog fuel in the platen press that can be used in conjunction with Figures 3 and 4 to determine what pressure is required in a platen press configuration to achieve a desired product moisture content. For example, application of 19.94 MPa to soaked hog fuel would result in a compression, C, of 0.7814. This is equivalent to a compression ratio of 3.575 which by Figure 4 would yield a product moisture content of 78.3% db, close to the experimental value of 76.4% db.

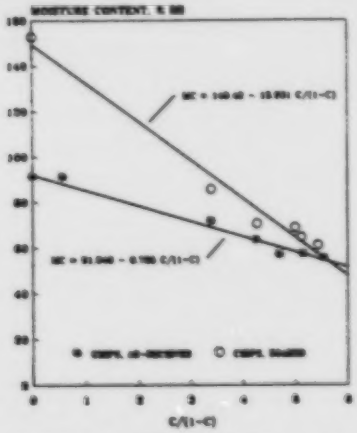

Figure 3 Correlation Between Moisture Content and C/(1-C) for Chips

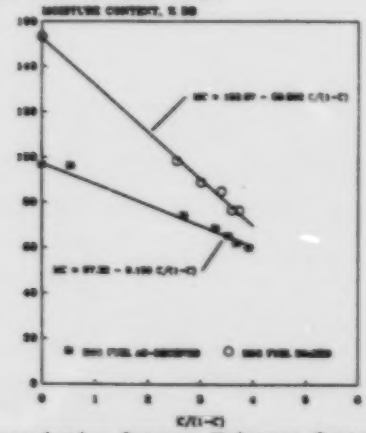

Figure 4 Correlation Between Moisture Content and C/(1-C) for Hog Fuel

CONCLUSIONS

1. Laboratory tests have demonstrated that the moisture content of hog fuel and chips of Western hemlock can be reduced to 38% wb and 32% wb respectively, by pressing in a platen press at 25 MPa. Much higher pressures are needed to achieve these low levels with either a roll or ram press because of less effective application of pressure to the material itself. Test results show that moisture contents much lower than those found in industrial use of existing presses can be achieved, albeit at higher pressure. The laboratory tests were done under near ideal conditions and it is doubtful that the test results could be duplicated in a full scale commercial press on a routine basis. However, the results suggest moisture contents of 40 - 45% wb are practical objectives for dewatering presses of improved design.

2. The correlations developed for dewatering of hog fuel and chips in a platen press are practical tools for application in industry. They are suitable for investigation of press performance and means of achieving lower product moisture contents through changes in operating conditions. Use of the correlation methodology for presses in industrial use is recommended since the results will assist the operator in understanding the effects of various operating changes, particularly those affecting material compression.

3. Dewatering presses should be set up to provide a set amount of mat compression under automatic control. Pressure is of importance, but secondary to compression ratio with respect to moisture removal. The optimum compression ratio will change with feed material. Where possible, the pressing area of a dewatering press should approximate a platen press configuration to achieve a high pressing effectiveness.

ACKNOWLEDGEMENTS

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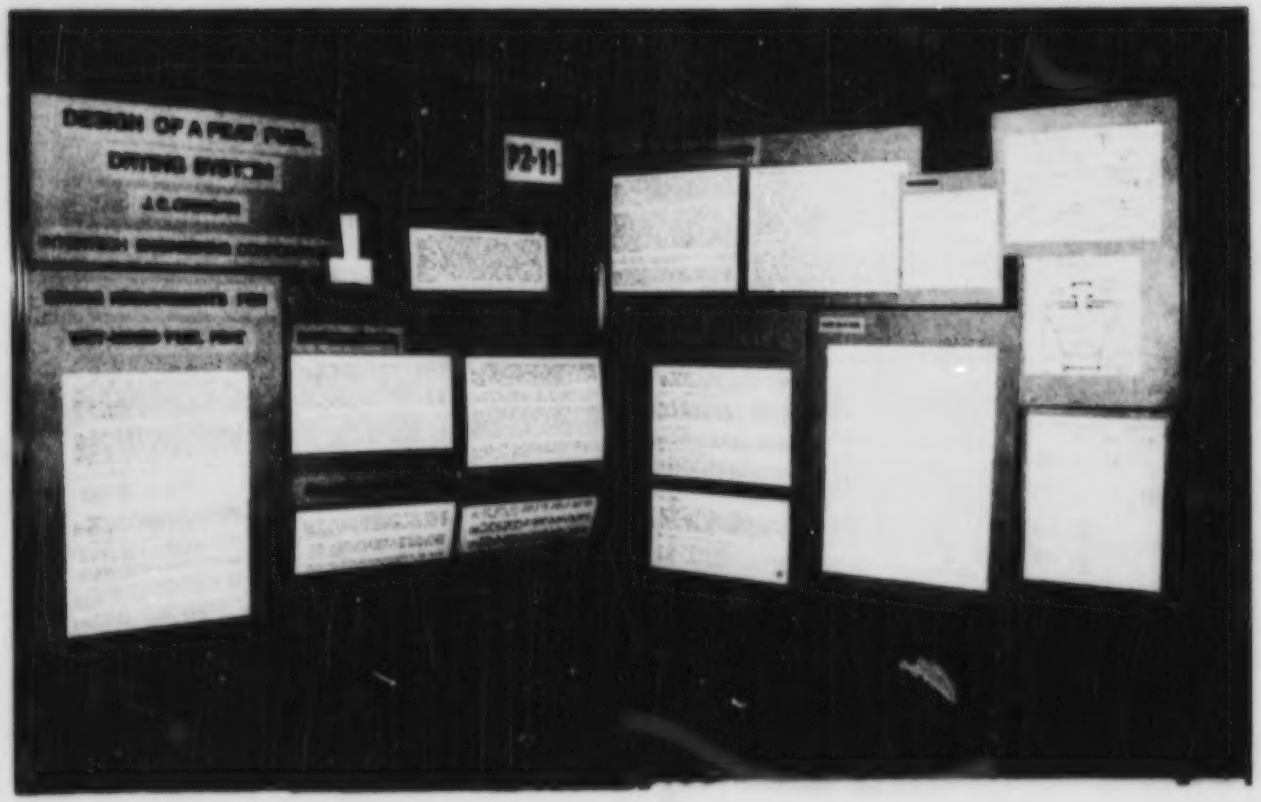
DESIGN OF A PEAT FUEL
DRYING SYSTEM
72-11

DEVELOPMENT AND DESIGN OF A PEAT FUEL DRYING SYSTEM

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A peat fuel drying system was designed to reduce the water content of peat fuel from 50% to 10% when operated as an integral component of a peat fuel processing system. The work was carried out under DSS Contract File No. 51SZ-23283 7-6063 for the Renewable Energy Programme of the Department, of Energy, Mines and Resources.
The drying system is described as a horizontal, tunnel type with flat belt conveyor, for outdoor operation, and with three distinct drying sections, namely: flue gas, warm air, and atmosphere. The wet peat fuel at 100°C (212°F) and 50% water, is initially dried with flue gas from the peat process system boiler at temperatures up to 260°C (500°F), then by warm air at 93°C (200°F) obtained from the condensing of wet steam in the process; and finally, by fresh air at 10°C (50°F), which together reduce the water content of the final peat product to 10% and with a temperature of 18.9°C (66°F).

On a conçu un système de séchage de la tourbe employée comme combustible, qui permet de réduire la teneur en eau de 50 % à 10 % lorsqu'il est utilisé en tant que partie intégrante d'un système de traitement de la tourbe. Ces travaux ont été réalisés en vertu d'un contrat passé avec le MAS (dossier n° 51SZ-23283-7-6063), dans le cadre du Programme d'énergies renouvelables mis en oeuvre par le Ministère de l'Énergie, des Mines et des Ressources.
Ce système de séchage, constitué d'un tunnel horizontal muni d'un convoyeur à courroie, est destiné à être utilisé à l'extérieur. Il comprend trois étapes distinctes de séchage, soit un séchage par les gaz de cheminée, un séchage à l'air chaud et séchage à l'air frais. La tourbe humide, portée à une température de 100 °C (212 °F) et renfermant 50 % d'eau, est d'abord séchée à une température pouvant atteindre 260 °C (500 °F) par les gaz de cheminée provenant de la chaudière du système de traitement de la tourbe; elle est ensuite séchée à l'air chaud à une température de 93 °C (200 °F) obtenue par condensation de la vapeur humide au cours du procédé. Finalement, on procède à un séchage à l'air frais à une température de 10 °C (50 °F). On obtient ainsi une tourbe renfermant 10 % d'eau, à une température de 18,9 °C (66 °F).

INTRODUCTION

A biomass dryer for fuel peat has been designed with some novel details for the re-use of energy recovered by condensers that are within the shell of the dryer. Where other energy-recovering systems usually require the addition of higher grade energy to continually upgrade the quality of the recovered energy, this system concentrates on ways to make reasonably efficient use of the low cost, low grade energy which is obtained when one starts with the waste heat from a high temperature process and then re-uses this heat as often as possible before it is degraded beyond any further use for drying.

In the system for which this dryer is planned, there is a wide range of temperatures. An affiliated process for heat treatment of a peat slurry supplies waste heat for the thermal drying system, while its own waste energy can be used for low temperature preheating of this same slurry from a near freezing temperature. With these multiple uses of heat, the systems use the energy at temperatures all the way from 300°C down to 0°C.

This dryer also covers a wide range of moistures, reducing the ratio of water per ton of solids total mass from 1t down to 0.11t.

The Report describes the features by which this biomass dryer can dry peat or other biomass quickly and safely at temperatures below 100°C.

Within an overall cost objective of below $3.00 per 1000 MJ of thermal energy in fuel peat, the cost objective for the thermal drying section is $0.50 per 1000 MJ.

OBJECTIVES OF THIS DRYER

The innovations described in this report provide new economies in the drying of peat fuel. In this particular example, it is assumed that the peat has been wet mined and then pressed after the low severity process noted above. The objectives are:

- Design a thermal drying system to reduce the moisture content of peat fuel from 50% to 10% by utilizing waste thermal energy from other parts of a wet mining peat fuel process plant.

- Optimization of the operating performance of the drying system to ensure economic use of energy.

Several conceptual designs were prepared and analyzed, to see which would best fit the objectives. In addition, several methods of conveyance of the peat fuel within the dryer were investigated. The final design of the drying system allows for the use of either purely mechanical or pneumatic conveyance, or a combination of both.

Detailed drawings of the total system and major components were prepared in sufficient detail to determine capital and operating costs, and also be used for procurement.

Calculations show that a peat fuel drying system module rated for handling 50,000 anhydrous tonnes of peat fuel/yr, with the entering fuel at a water content of 50% and a leaving water content of 10%, can be built for a capital cost of $400,000.00, and a drying cost, including depreciation, finance, maintenance, energy and labour, of the order of $0.375/1,000MJ ($0.39/MBtu) of fuel produced, when using waste thermal energy from a peat slurry processing system.

Unit costs of energy for the system are based on a sliding scale of prices which depend upon the temperature of the waste flue gas and its average value to both the supplier and user system.

THE DRYING REQUIREMENTS FOR WET-MINED FUEL PEAT

Peat has long been used as a fuel source except in Canada, where other sources of energy have been abundant. Peat in the bog contains 90% water so that use of fuel peat depends upon economical dewatering. In general, the dewatering of peat has, until recently, been accomplished by drainage, excavation, spreading, and solar drying, (the so-called conventional harvesting). This method is possible only during mild and reasonably dry weather thereby limiting its practicability.

Due to the collaboration of NRC's Energy Division and the Laboratoire de Recherches sur les Technologies de Conversion (Universite de Sherbrooke) a process has been developed for the removal of water from the peat which makes possible the concept of wet mining and thermomechanical treatment. The net result of this process is a modified peat material which can be mechanically dewatered into a cake having as little as 50% water.

This approach has the following advantages over alternate methods:

- year-round operation even in cold climate;
- rapid processing;
- no major pollutants or sub products;
- low energy consumption.

However, in order for the dewatered peat to be useable as a fuel, further reduction in the water content is needed. The water content can be reduced from 50% to 10% by the use of this energy-efficient thermal drying system.

The highlights of this work are as follows:

- The drying system can accomplish water removal from mechanically dewatered peat fuel to a level of 10% or better, at an exceptionally low energy cost.

- The drying system plays a vital role in a total peat fuel processing system in that an alternative to coal becomes economically feasible.

The drying system utilizes existing and readily available components, materials, and technologies, and is operable in outdoor locations during the year-round climate conditions of northern Ontario or equivalent climate regions.

Combined with the low severity heat treatment and wet pressing processes, this thermal drying system makes it economically viable to produce peat fuel by wet mining.

FEASIBILITY AND OPTIMIZATION

The operator of the dryer will have manual control over five key operating details. Fortunately the optimum conditions for each one can be recognized easily and they come as broad peaks rather than sharp points.

Thickness of Peat Bed on Conveyor

This has to be thick enough to prevent by-passing. Reported experience with various kinds of thick bed dryers shows that most of the heat and mass transfers occur within a 10 cm band, so that a bed depth of 20 cm should be sufficient to obtain full conversion of the superheat of the air.

Conveyor Speed

The conveyor speed is controlled by a variable speed drive. It will be set to process the hourly tonnage of peat which matches the total energy conversions of the dryer.

Gas and Air Velocities

Velocities should be as high as possible to maximize the drying capacity. The upper limit will be limited by the dusting which occurs and will be higher at the wet end than the dry end of the dryer. It will be adjusted by experience.

Heat Input

The heat input can be varied by changing the temperature or the flow rate of the flue gas. Increasing the heat will obviously increase the drying capacity but too large an increase will reduce the percentage recovery of the condenser. Optimum overall performance will involve a high energy input and reducing the condenser performance to, say, 70% recovery instead of 85%.

Relative Size of Sections of the Dryer

The flexible partitions between different sections of the dryer can be moved to optimize the relative capacities. For instance, the partition between the once-through fresh air and the recirculating air could be moved in either direction to increase the capacity of one at the expense of the other.

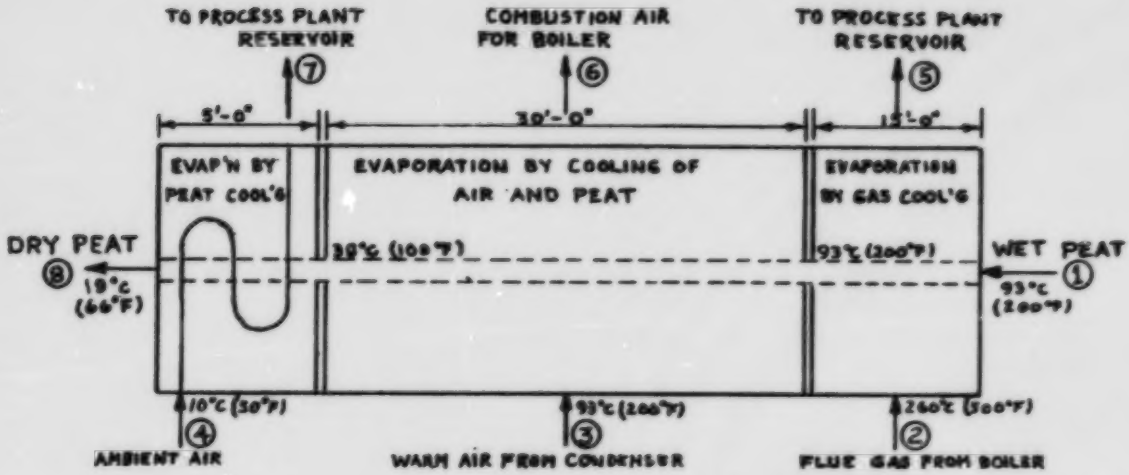
WHY ENERGY RECOVERY IS NEEDED

Peat drying requires the savings of a recuperative type of dryer to reduce energy costs because the quantity of water to be removed is greater than with other products, and because the dried product is cheaper than most commodities. The long operating season planned for wet mining of peat tends to favour spending extra on the drying equipment, instead of using the cheaper, but wasteful, equipment which might be selected for drying a seasonal farm crop. It is expected that drying operations will continue even into winter, as long as the waste heat from the dryer is sufficient to keep a section of the peat slurry pond unfrozen.

DESCRIPTION OF THE DRYER

The Intertech dryer is a new kind of tunnel dryer which makes use of recovered energy to reduce its fuel costs. Tunnel dryers carry the product on woven steel conveyors, with a high volume of hot gas blown vertically through the product. Easily controlled variations in gas temperature, gas velocity, conveyor speed, and thickness of product make tunnel dryers adaptable for a wide variety of products, moisture ranges and heat sources.

MASS AND ENERGY FLOW DIAGRAM
FIGURE # 1



NOTE: SEE MASS & ENERGY FLOW DATA SHEET FOR VALUES AT NUMBERED LOCATIONS

Key Features for Energy Efficient Drying

Condensers are key elements in improving the efficiency of many energy systems, ranging from steam engines developed in the early part of the nineteenth century, to air conditioners which found widespread use early in the twentieth century. The principle of converting humidity into the more useable sensible heat has not yet been widely used for drying. Most drying systems are either fast systems, using a high temperature energy on a once through basis, or slow systems which use solar energy at a low temperature. This system uses a range of different temperatures, the higher being in the hot flue gas which is salvaged from the effluent of a high temperature system. It also uses the intermediate temperature heat which is obtained by warming of air in the condenser.

High Flow Rates Needed for Warmed Air

When condensers are used for recovering the latent heat of water vapour, high flow rates are needed in the side which is being warmed. For instance, in the case of the dryer, where flue gas at a dewpoint of 71°C gets cooled to 38°C, each kg of hot gas supplies enough heat to warm 21 kg of air from 10°C to 43°C. Consequently, the dryer uses a large flow of fresh air, most of which gets heated once, then is blown through the peat for drying, and then is ducted to the peat slurry pond, or to the preheating of peat slurry.

EMR-IEC PEAT FUEL DRYER

The hot flue gas which enters the end of a long condenser will be condensing at gradually lower temperatures on its way through. In the hotter half of the condenser, air can be recirculated several times through the condenser, through the peat bed and back to the condenser. Its rising temperature improves the drying power but its rising humidity counteracts this improvement. Eventually, the hottest and most humid portion of this air gets transferred to the furnace for combustion. At this point its temperature and dewpoint are near 65°C. The combustion adds further moisture, which will later be returned to the dryer as heat from a condenser.

Hot flue gas returns to the dryer at up to 260°C, where it takes one pass through the dryer.

The final section of the dryer uses unheated air. The evaporation provides a rapid cooldown. This section can be quite small because most of the cooling occurs quickly and it is not necessary to fully cool the peat since dried peat does not self-ignite.

PEAT AS A FUEL

The fuel used in the furnace for heat treatment and drying of the peat would be a portion of the dried peat. It can be burned in a pellet form or pulverized.

Possible Pelletizing Before Drying

Common sized pellets of approximately 1 cm diameter are larger than the optimal for quick heat and mass transfer in a dryer. Loose flocculent peat is ideal in these regards, but its light weight makes it easily airborne, which limits the gas velocities in the dryer. A compromise would be to press it into spaghetti-like pellets of 3 mm diameter, small enough for quick drying, but dense enough to avoid unwanted pneumatic conveying in the dryer. These small pellets would be easily pulverized, but they might not even need pulverizing for burning in a pulverized coal furnace. They would also be easily burned in small furnaces and stoves.

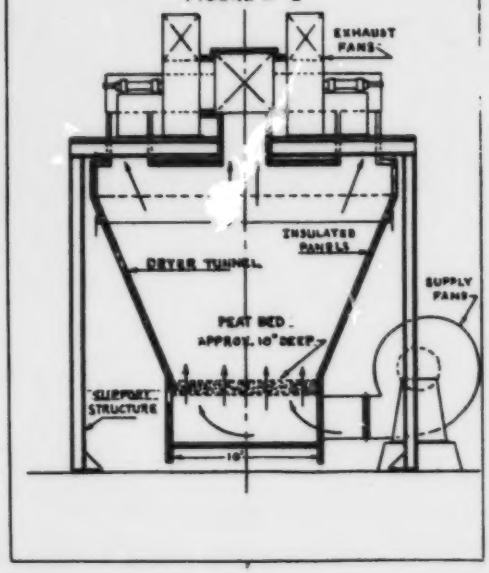
Peat pellets are an easily-burned fuel, with a heat value similar to lignite coal. The exhaust gas from a peat fire contains only one tenth on average as much sulphur dioxide as the gas from some varieties of coal.

With minor changes, this dryer could become a stand-alone device with its own furnace, instead of using waste heat from another process. For instance, wet mining of peat is not the only alternative to the traditional field harvesting method. Another approach is to drain an area of bog and then quarry the peat with excavating equipment. The drainage could reduce the moisture content from 90% to 80%. From that point there could be some significant solar drying, but not enough to finish the drying. The thermal dryer is still needed. This kind of peat production would greatly reduce the wind losses which occur in the harrowed field method, where up to 20% of the peat blows away.

When improvements in the process keep cutting away at production costs, we reach the point where a component such as thermal drying amounts to less than 15% of the f.o.b. value of the peat, while the uncontrollable cost for transportation might match the total production cost. Local co-generation of electricity can get around the shipping costs. Wherever there is a nearby market for electricity, it seems attractive to produce it right at the bog. In this case, the generating station would supply the waste heat for drying and would be a market for much of the peat.

We believe that a peat fuel development combined with co-generation will be the ideal starting point for Canada's peat fuel industry.

TYPICAL CROSS SECTION
PEAT FUEL DRYER
FIGURE # 2



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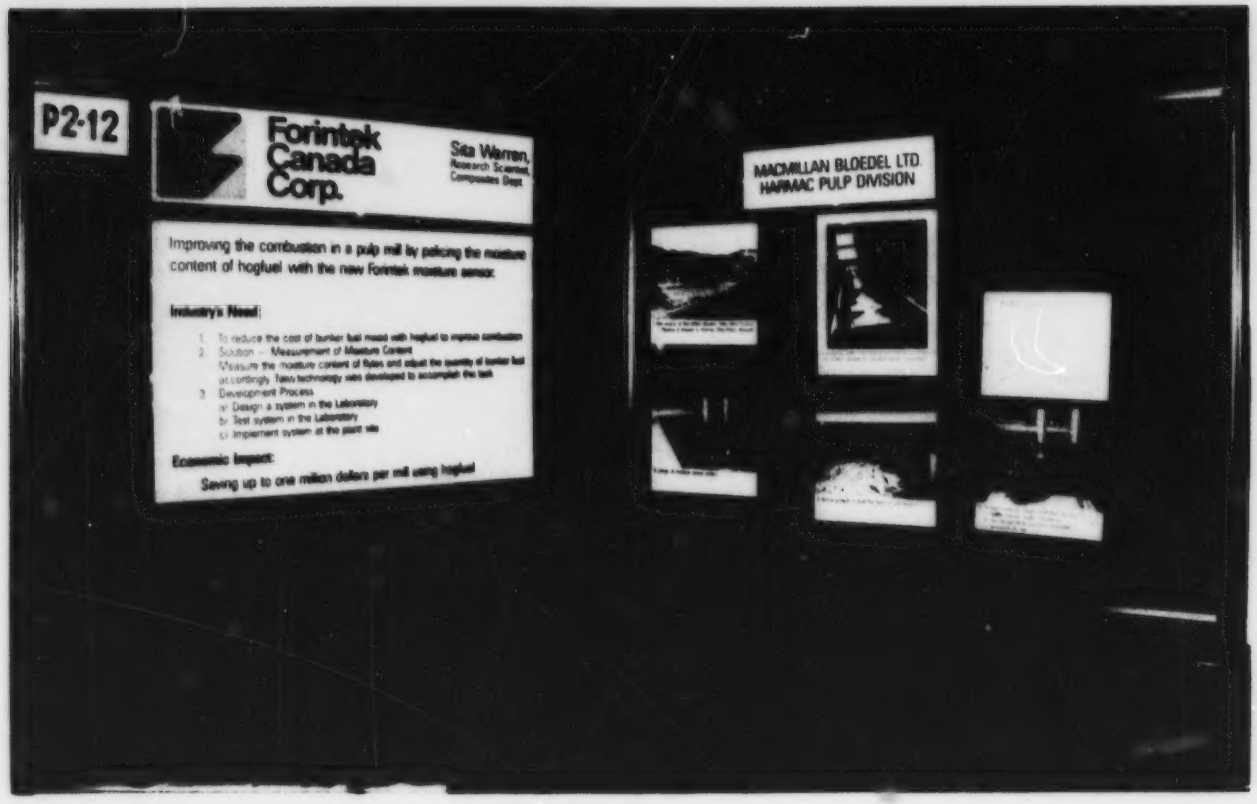
MASS AND ENERGY BALANCE
FOR ONE 50,000 t/yr DRYER MODULE

	Peat Solids kg/hr	Water & Vapour kg/hr	Dry Air & Gas kg/hr
Inlet			
Wet Peat (1)	10,000	10,000	------
Flue Gas (2)	------	1,430	33,113
Hot Air (3)	------	1,497	195,500
Ambient Air (4)	------	69	9,072
TOTAL	10,000	12,996	237,685
Outlet			
Dry Peat (8)	10,000	1,005	------
Flue Gas (5)	------	5,153	33,113
Warm Air (6)	------	6,641	195,500
Cold Air (7)	------	195	9,072
TOTAL	10,000	12,994	237,685

Energy Flows

Inlet	
Wet Peat (1)	5.86 MJ/hr
Flue Gas (2)	13.53 MJ/hr
Hot Air (3)	25.87 MJ/hr
Ambient Air (4)	.43 MJ/hr
TOTAL	45.69 MJ/hr
Outlet	
Dry Peat (8)	.48 MJ/hr
Flue Gas (5)	16.27 MJ/hr
Warm Air (6)	28.00 MJ/hr
Cold Air (7)	.92 MJ/hr
TOTAL	45.67 MJ/HR


P2-12
Forintek Canada Corp.
Sita Warren,
Research Scientist,
Composites Dept
Improving the combustion in a pulp mill by policing the moisture content of hogfuel with the new Forintek moisture sensor.
Industry's Need:
1. To reduce the cost of bunker fuel mixed with hogfuel to improve combustion
2. Solution – Measurement of Moisture Content
Measure the moisture content of fules and adjust the quantity of bunker fuel accordingly. New technology was developed to accomplish the task
3. Development Process
a) Design a system in the Laboratory
b) Test system in the Laboratory
c) Implement system at the plant site
Economic Impact:
Saving up to one million dollars per mill using hogfuel
MACMILLAN BLOEDEL LTD.
HARMAC PULP DIVISION

IMPROVING THE COMBUSTION PROCESS IN A PULP MILL BY POLICING THE MOISTURE CONTENT OF HOGFUEL WITH THE NEW FORINTEK MOISTURE SENSOR

S.R. Warren
Forintek Canada Corp., Vancouver, B.C.

The new Forintek moisture sensor was used to monitor the moisture content of hogfuel contained in flytes and fed to the boiler in a continuous flow. This information on the moisture content was used to control the quantity of bunker fuel injected to the hogfuel for proper combustion.

The new Forintek moisture sensor has been used to accurately measure the moisture content of lumber and veneer. The sensor has been successfully sorting lumber under 20% moisture content at the West Fraser plant (Williams Lake). Based on lumber grade and recovery, the saving by sorting into moisture content classes is $10 per thousand. Energy saving was calculated to be 22 percent.

This method of accurately measuring moisture content holds considerable promise for improving the combustion process in pulp and paper mills that utilize large quantities of hog fuel in their boilers. The moisture content must be measured to permit appropriate furnace adjustment, and to reduce the amount of fossil fuel injected into the mix. Poor control of the boilers leads to inefficient combustion and unacceptable smoke emissions.

Short Description of Boilers at Steam Plant

There are 4 boilers generating 60% of the steam requirement for the pulp and paper plant at Harmac (McMillan Bloedel). The steam requirement varies from season to season.

Example:

	January	May
Steam requirements	45%	37%

The boilers vary in design (figures 1, 2) and also in the amount of B.T.U. or lbs/steam produced per hour. All the boilers are equipped with oil guns placed at various intervals along the sides. They are also located at different heights.

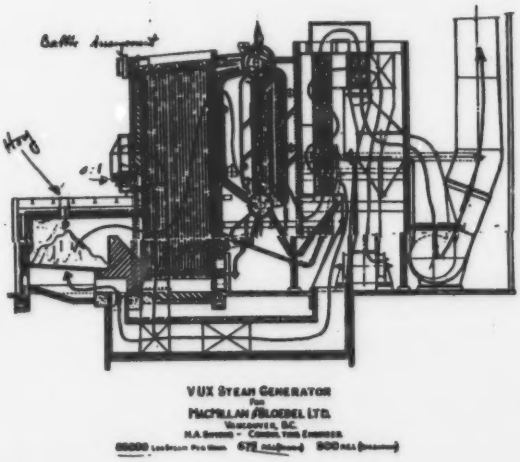


Fig. 1

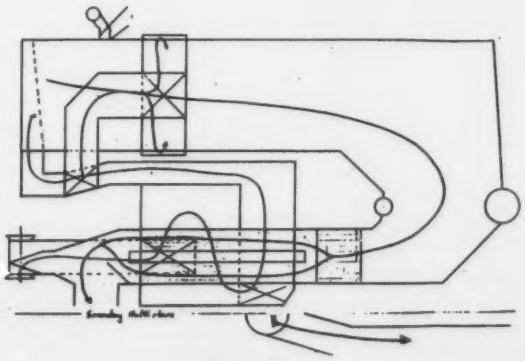


Fig. 2

The largest of them all is Boiler No. 9 which has 8 oil guns. Bunker fuel is released as required and controlled according to the B.T.U, desiried to keep the steam plant operation. This is not done accurately. The two Vux boilers generate, or are rated, at 80,000 lbs/hrs. Vux No. 3 operates at 120,000 lbs/hr. Boiler No. 9 is rated at 450,000 lbs/hr. These figures are the maximum ratings but the energy figures are never achieved.

Energy Mix

The mix for fuel varies according to the following constituents:

Months	Hogfuel (%)	Bunker Fuel (%)
January	74	26
May	88	12

Note: For the month of May the hogfuel moisture content was lower than that of January and less bunker fuel was required.

Method

A moisture system was constructed at the mill to suit their specific needs (Figure 3). An infrared (5000 Watt) heater was installed in the frame. Two teletemp model 44-2MHX temperature sensor gave the initial and final temperature of the hogfuel. The temperature difference was correlated to oven dry moisture content.

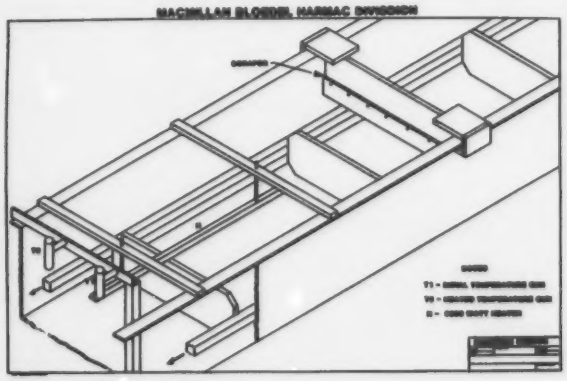


Fig. 3

A scraper was designed and installed inside the flyte to level the bed of the hogfuel which was transported to the boiler, so that the thickness was uniform throughout the sample. The flyte spacing was 3 ft. apart and the speed at which they travel is 120 ft/min. (Figure 3).

The signal from the temperature sensors was transmitted to the IBM and the output signal was proportional to moisture content. This signal was transmitted to the mill computer to control the quantity of fossil fuel. The signal from Forintek computer was digital and the signal from the mill's system was analog. A converter for converting the digital signal to analog had to be designed and wired up to fit the two computer systems (Figure 4). Bunker fuel was regulated according to the average moisture content of ten flytes.

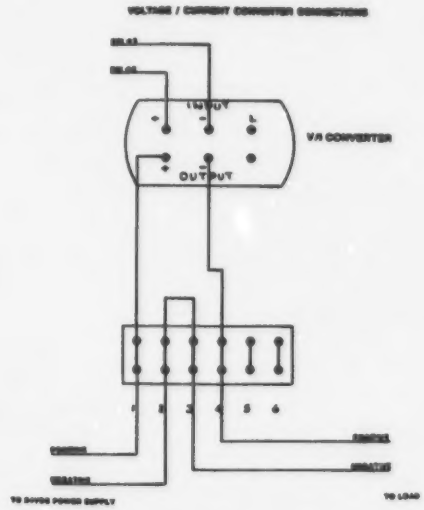


Fig. 4

Conclusion

The sensor performed well for hogfuel and showed a good correlation between actual moisture content and temperature. This type of control system, can improve the combustion process and result in a reduction in the quantity of fossil fuel used. The economic saving to this plant is substantial, and this commercial prototype will lead to more pulp mill utilizing their residue for power consumption.

P2-13
CRIQ
CENTRE DE RECHERCHE
INDUSTRIELLE DU QUÉBEC

ESSORAGE DE BOUES DE PATES ET PAPIER

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Québec, Canada

Des essais de pressage de boues de pâtes et papier, au moyen d'un pressoir rotatif de 90 po de diamètre, ont démontré que la boue obtenue devenait un combustible presque aussi intéressant que les résidus de scieries.

Tests on pressing pulp and paper stored sludge using a 90 po ring press showed that the resulting sludge was a fuel with almost as much potential as sawmill waste.

INTRODUCTION

Des essais de pressage de boues de pâtes et papier entreposées datant de deux (2) semaines à cinq (5) ans ont été faits au cours de l'été 1988, au moyen d'un pressoir rotatif de 90 po de diamètre.

Une production allant jusqu'à 125 tonnes anhydres a été obtenue avec une consistance de 45% de matières sèches. Des essais de combustion ont démontré que cette boue devenait un combustible presque aussi intéressant que les résidus de scieries. Dépendant du type et des quantités de boues entreposées, une installation de pressage s'avère rentable et pourrait s'amortir sur une période allant d'un (1) an à trois (3) ans dépendant de la quantité requise à la bouilloire.

RESULTAT

Une famille de courbes illustrant la rentabilité d'essorer les boues entreposées dépendant des caractéristiques de ces boues.

ESSAIS D'ESSORAGE DES BOUES ENTREPOSEES

Introduction

De plus en plus au Canada, on utilise les boues de pâtes et papier comme combustible dans les chaudières à vapeur.

Il reste néanmoins d'immenses quantités de boues entreposées en piles dans les cours des papeteries. Ces boues sont lavées graduellement par les eaux de pluie et finissent par polluer les cours d'eau.

Ce projet avait pour but de démontrer qu'en plus de solutionner ces problèmes, il était économiquement avantageux d'essorer ces boues entreposées afin de les utiliser comme combustible dans les chaudières à vapeur.

Préparation

Il existe différents types de pressoirs utilisés pour essorer les boues de pâtes à papier à partir du clarificateur ou du filtre épaississeur. Par contre, nous n'avons pas trouvé de cas où une presse était utilisée pour presser les boues entreposées.

Les raisons principales sont d'une part qu'un tel pressoir doit avoir la capacité de production et de siccité requis pour justifier les installations de récupération et de manutention et d'autre part que le pressoir ne soit pas trop vulnérable aux matières étrangères trouvées dans les dépotoirs de boues.

Il existait au CRIQ un pressoir rotatif de type ring press de 90 po de diamètre qui avait été construit pour des essais d'essorage de pulpe de betteraves. Ce pressoir avec son canal de 6 po serait apte à presser ces boues. Il fallait par contre lui apporter des modifications pour mieux l'adapter au pressage de boues. Les modifications suivantes furent donc apportées:

a) l'entraînement de la presse fut modifié de façon à doubler la vitesse de rotation. Pour ce faire, les cylindres existants de 12 po de diamètre furent remplacés par des cylindres de 8 po de diamètre;
b) le système de vis d'alimentation fut modifié pour mieux manipuler des boues telles que l'on retrouve dans les dépotoirs;
c) le système de sortie fut modifié pour assurer un meilleur contrôle de pression afin de mieux maintenir la siccité visée de 45%;
d) puis un système de trémie et convoyeur fut conçu et fabriqué afin de garantir un débit continu à la vis d'alimentation;
e) enfin un système de contrôle de l'opération y incorporant un système d'acquisition de données fut installé afin de mieux contrôler les différents paramètres tels que:

- pression d'entrée
- pression de sortie
- vitesse de rotation
- pression sur cylindre d'entraînement.

Tests en laboratoire

Une quantité de boues non essorées fut obtenue du dépotoir de la papeterie d'Abitibi Price à Alma et fut essayé dans le pressoir au laboratoire de Ste-Foy. Après ajustements des divers systèmes, une production très intéressante fut obtenue avec des pointes allant jusqu'à 125 tonnes anhydres par jour. La siccité à la sortie se situait entre 40 et 45% de solides.

Tests en usine

Le pressoir, la trémie et les convoyeurs d'alimentation et de sortie furent déplacés vers l'usine d'Abitibi Price à Alma. Le tout fut installé sur une ancienne aire de stationnement asphaltée. Comme les boues entreposées contenaient de nombreux corps étrangers tels que pierres, billes de bois et autres déchets provenant de l'usine de pâtes à papier, il fallut procéder à un prétamisage des boues à essorer.

Un contrat fut donc donné à un entrepreneur local qui fit le tamisage à 2 po et le transport du dépotoir au site d'essorage d'une centaine de tonnes de boues de trois (3) types différents:
Type no 1: boues d'environ 2 mois
Type no 2: boues de 2 ans
Type no 3: boues de 5 ans

Les taux de production ont varié de 25 à 75 tonnes anhydres par jour pour des consistances de 34 à 48% de matières sèches dans le gâteau à la sortie. Quelques 21 essais ont été faits sur les trois (3) types de boues ainsi que des mélanges de différents types de boues.

Enfin, des essais de combustion ont été faits dans une chaudière de l'usine en dosant de la boue essorée avec des résidus de scieries. Ces essais ont démontré que la valeur de la boue comme combustible était si près de celle des résidus de scieries qu'aucune déviation ne fut perceptible au niveau des lectures de pression de la chaudière.

Les calculs des valeurs énergétiques qui suivent furent donc calculées à partir des valeurs calorifiques des boues telles que mesurées en laboratoire.

ANALYSE DE LA VALEUR ENERGETIQUE DE BOUES DE PATES ET PAPIER ESSOREES

Introduction

Dans les sections qui vont suivre, nous allons développer un modèle avec toutes les hypothèses inhérentes dans le but de quantifier les gains créés par l'essorage et de visualiser sous forme graphique les limites entre lesquelles il y a atteinte d'une rentabilité accrue. De plus, ces graphiques vont nous permettre de déterminer des niveaux optimum d'essorage à atteindre en fonction des paramètres les plus importants qui régissent la rentabilité d'un tel procédé.

Définition du concept de la valeur économique théorique de la boue essorée

De façon rigoureuse, la valeur économique théorique peut être définie de la façon suivante:

$$\left[\begin{array}{c}\text{Valeur économique}\\ \text{théorique}\\ \text{de la boue essorée}\end{array}\right] = \left[\begin{array}{c}\text{Valeur en tant}\\ \text{que combustible}\end{array}\right] - \left[\begin{array}{c}\text{Coût}\\ \text{d'essorage}\end{array}\right] + \left[\begin{array}{c}\text{Coût}\\ \text{d'enfouissement}\end{array}\right] - \left[\begin{array}{c}\text{Coût supplémentaire}\\ \text{de maintenance}\end{array}\right]$$

Toutes les valeurs ci-haut mentionnées peuvent être exprimées en $ par tonne humide ou par tonne sèche (anhydre). Dans la littérature, l'on exprime ces termes surtout avec les unités de $/tonne anhydre, et nous allons faire de même dans le texte.

Valeur en tant que combustible

Cette valeur est calculée par l'expression suivante:

$$\left[\$/\text{tonne anhydre}\right] = \left[\frac{\text{Poids}}{\text{Tonne}}\right] * \left[\begin{array}{c}\text{Pouvoir calorifique}\\ \text{supérieur (PCS)}\end{array}\right] * \left[\begin{array}{c}\text{Efficacité globale}\\ \text{de l'équipement de}\\ \text{production de vapeur}\\ (\eta)\end{array}\right] * \left[\begin{array}{c}\text{Coût de l'énergie}\\ \text{de remplacement}\\ (\$/\text{MMBTU})\end{array}\right]$$

$$\boxed{\left[\frac{\$}{\text{Tonne anhydre}}\right] = \frac{(2\,000 * \text{PCS} * \eta)}{10^6} * \frac{\$}{\text{MMBTU}}}$$

où:
PCS = Pouvoir calorifique supérieur en BTU/livre.
η = Efficacité globale de l'équipement de combustion des résidus de bois.
$/MMBTU = Coût de l'énergie de remplacement pour un million de BTU, après inclusion de l'efficacité de cet équipement.

Le nombre de tonnes anhydres contenues dans une pile de boues est relié au nombre de tonnes humides par la relation suivante:
no tonne anhydres = no tonnes humides * $\left[1 - \frac{\%\text{ d'eau}}{100}\right]$
où % d'eau = teneur en eau base humide (valeur moyenne);
% solide = 100 - % d'eau.

La masse de la pile de boues est égale au volume de celle-ci multiplié par la densité moyenne (en livres/pi^3) de la boue.

Ainsi, il y a trois (3) paramètres influant directement sur la valeur de la boue en tant que combustible. La quantité unitaire utilisée comme référence sera dorénavant la tonne anglaise.

Quant à l'efficacité globale de l'équipement de combustion, elle est grandement fonction de la teneur en eau dans le combustible, étant donné que la quantité de chaleur par unité de poids est moindre et qu'une bonne partie de l'énergie disponible sert à vaporiser l'eau présente (température de flamme moins élevée) bien qu'il peut avoir condensation ultérieure d'une portion de ces vapeurs. La figure 1 suivante tirée de la référence identifiée illustre l'efficacité typique développée par une bouilloire en fonction du contenu en eau du combustible exprimé sous la base humide. En guise d'information supplémentaire uniquement, la figure 2 tirée de la même référence illustre la variation typique de la capacité d'une bouilloire en fonction du contenu en eau. En premier lieu, la capacité de l'équipement diminue à cause du plus grand volume de gaz créé par l'évaporation de l'eau et par une baisse de l'efficacité globale d'échange, et aussi par une baisse de performance du système d'épuration des gaz de combustion créée par le plus grand volume de gaz dû à l'évaporation. L'ampleur de l'impact de ce phénomène est cependant particulier à chaque bouilloire.

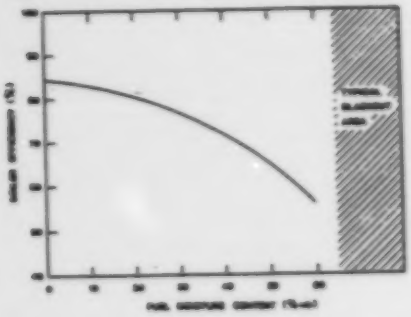


Figure 1

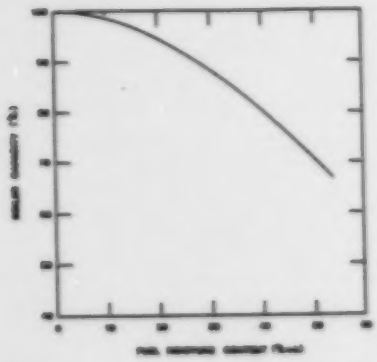


Figure 2

Figures tirées de la référence: "ESTABLISHMENT OF OPERATING PARAMETERS FOR EFFECTIVE MECHANICAL DEWATERING OF WOOD RESIDUES", préparé par B.H. Levelton et Ass. Ltd, Vancouver (W.C. Edwards et F. Tom) pour le compte de Energie Mines et Ressources Canada.

Avec l'utilisation d'un combustible plus humide, il est possible que l'on soit obligé d'opérer une ou des bouilloires supplémentaires, tout dépendant de la charge à rencontrer. Evidemment, il y a une limite supérieure dans le contenu en eau qu'une bouilloire peut accepter, sinon elle s'étouffe, et généralement cette limite se situe un peu au-delà de 60%.

Quant au pouvoir calorifique supérieur, il est bien entendu que la portion de "matières incombustibles" présentes (cendres) interfère sur celui-ci. La façon la plus juste pour déterminer la valeur calorifique des échantillons prélevés dans la pile de boues (par unité de masse de produit anhydre), c'est par des mesures à l'aide d'une bombe calorimétrique, laquelle nous permet de connaître par ricochet le pourcentage de cendres.

Quant à la dernière variable intervenant dans l'expression, c'est-à-dire, le coût de l'énergie de remplacement ($/MMBTU), il est particulier à chaque installation, à chaque moulin comme ainsi dire. Selon des contacts entrepris, certains moulins à papier paient leur énergie autour de 2,5 $ le million de BTU, l'équivalent d'aussi peu 7/8 cent pour chaque kW-h (sous le tarif domestique, l'on paie presque 5 cents avec la taxe), alors que d'autres installations peuvent payer leur énergie plus cher.

Coût d'essorage

Pour établir la courbe du coût d'essorage en fonction de la teneur désirée en matières solides, l'on s'est basé sur les hypothèses suivantes:

- le coût pour essorer à 40% est estimé être de 40 $ CDN la tonne anhydre;
- la capacité d'une presse essoreuse (en tonne anhydre par heure) chute par un facteur 2 lorsqu'on porte la teneur de solides à 50%, ce qui crée un coût unitaire de 80 $ la tonne;
- la capacité d'une presse augmente d'environ 25% lorsque la teneur en matières solides n'est que de 35%, faisant en sorte que le coût est de 33 $ la tonne anhydre;
- le coût pour porter la teneur à 45% est estimé être autour de 56 $ la tonne anhydre.

La courbe du coût d'essorage en fonction de la teneur en matières solides peut être assimilée à une quadratique.

Coût d'enfouissement

Si la facture reliée à l'enfouissement (qui peut être obligatoire dans certains cas suite à des règlements municipaux ou autres)

est éliminée grâce à la "plus value" donnée à la boue par une presse, nous pensons que ce montant doit s'ajouter à la valeur énergétique de ce combustible en tant que telle.

Selon des contacts entrepris, le coût d'enfouissement peut atteindre facilement 10 dollars le mètre cube. En supposant une densité moyenne du produit dans la pile de 40 livres le pied cube et une consistance de 30%, l'on en arrive à un coût de grosso-modo 48 $ la tonne anhydre, ce qui est loin d'être négligeable, par rapport à la valeur énergétique comme telle ou au coût d'essorage, comme on le verra plus loin. Cependant, nous n'allons pas considérer ce paramètre dans les calculs qui a conduit à l'obtention des graphiques qui suivent, car il est de pratique courante pour les gens du milieu de faire abstraction de ce coût dans l'analyse économique de ce sous-produit, lequel peut devenir un combustible intéressant.

Coût de maintenance supplémentaire

Cet item est beaucoup plus difficile à évaluer, car en général, une bouilloire ne peut fonctionner si elle est alimentée seulement en boue, c'est-à-dire, le combustible est généralement constitué d'un mélange de brans de scie, d'écorces, de boues et d'huile légère ou lourde.

Tout de même, les informations suivantes ont été obtenues pour une bouilloire à vapeur développant une capacité de 75 000 livres par heure et dont le combustible est en gros constitué de:

. 8,3 BDT/jour de brans de scie;
. 14,9 BDT/jour de boues;
. 61,6 BDT/jour d'écorces;
. le reste du combustible est du mazout (BDT: "Bone dry ton" ou tonne anhydre).

Les principales composantes du coût de maintenance supplémentaire sont les suivantes:

. nettoyage "DUTCH OVEN"
  $50 \frac{\text{sem.}}{\text{an}} * 3 \text{ hommes} * 25 \frac{\$}{\text{h}} * 8 \text{ h} = 30\,000 \$/\text{an}$
. sani-mobile
  $4 * \frac{6\,000 \$}{\text{nettoyage}} = 24\,000 \$/\text{an}$
. boîte à cendres
  $2\,1/2 \frac{\text{voyages}}{\text{sem.}} * \frac{200 \$}{\text{voyage}} * \frac{500 \$}{\text{semaine}} = 25\,000 \$/\text{an}$
. usure de la tuyauterie de soufflage et des cyclones, convoyeurs à cendres, alimenteur, etc.: environ 20 000 $/an
. produits chimiques pour nettoyer l'extérieur des tubes (dû à un point de rosée plus bas): 5 000 $/an

TOTAL: environ 105 000 $/an

Pour le cas concerné, la consommation de boue représente entre 15 et 20% de la consommation totale de résidus de bois (brans de scie, écorces et boues). Ce qui est inconnu de la part des utilisateurs, c'est la proportion des coûts de maintenance supplémentaires reliés directement à la combustion des boues; compte tenu de la composition de celles-ci, nous allons supposer que la proportion est de 50% des coûts totaux énumérés ci-haut (valeur plausible). Sur cette base, ceci représenterait quelque 50 000 $ par année, alors que la consommation de boue aura été grosso-modo 5 000 tonnes anhydres. Selon ces hypothèses, ceci entraînerait un coût de maintenance supplémentaire de quelque 10 dollars la tonne anhydre.

VALEUR OPTIMALE D'ESSORAGE

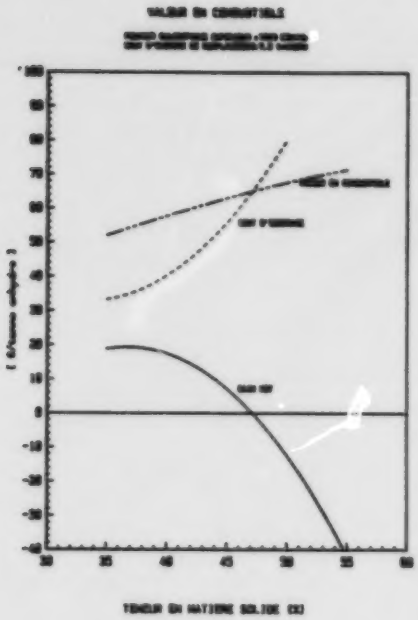
Puisque le coût d'enfouissement et le coût de maintenance supplémentaire sont vraiment particuliers à chaque installation, comme nous l'avons dit précédemment, nous n'allons pas considérer ces deux composantes dans l'analyse qui suit. Par conséquent, nous allons mettre en relief que les deux (2) autres composantes restantes, soit la valeur énergétique de ce carburant en tant que telle et le coût d'essorage. Comme la valeur énergétique augmente (de façon presque linéaire) avec la teneur en matières solides, mais de moins en moins vite, contrairement au coût d'essorage qui croît très rapidement, il y a donc un point où un maximum est atteint dans la valeur ou le gain net.

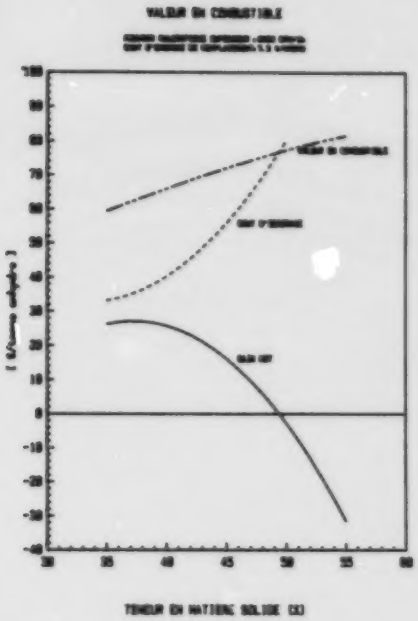
Dans les six (6) graphiques qui suivent, la valeur énergétique (en tant que combustible), le coût d'essorage et le gain net sont illustrés en fonction de la teneur en matières solides dans la boue.

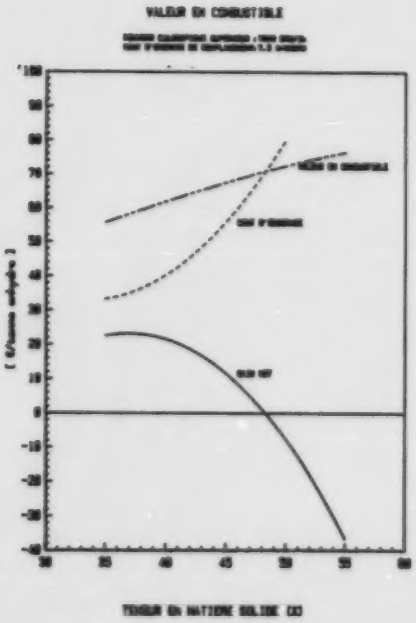
Nous avons donc six (6) groupes de trois (3) graphiques correspondant à 6 valeurs de coûts de l'énergie de remplacement (2,5 à 15 $ du million de BTU) et pour 3 valeurs du pouvoir calorifique supérieur (7 000, 7 500 et 8 000 BTU par livre de carburant anhydre).

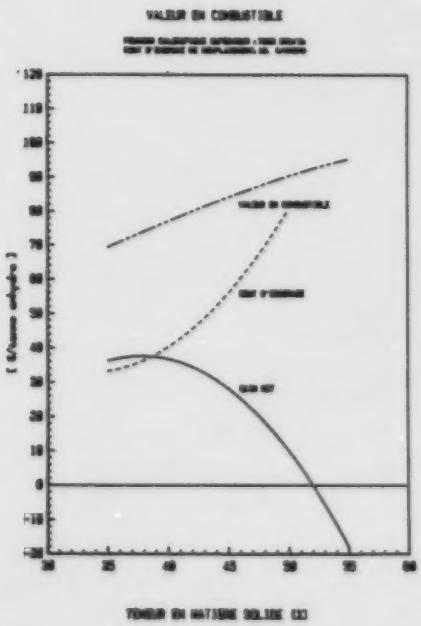
Sur la base des hypothèses présentées précédemment, les observations que l'on peut tirer sont en gros les suivantes:

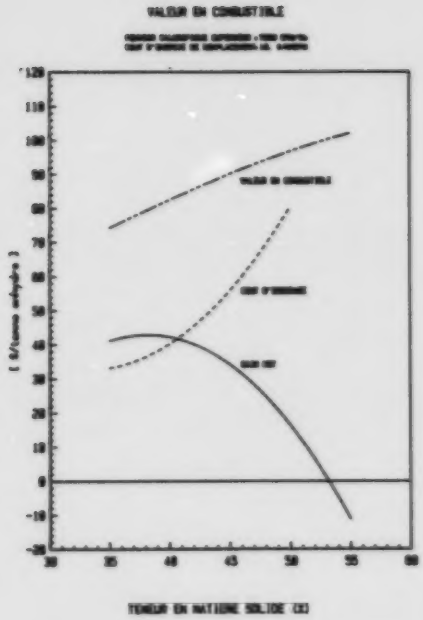
. pour de faibles valeurs du coût de l'énergie de remplacement, il semble qu'il y ait intérêt à essorer les boues au minimum acceptable par la bouilloire, quelque chose entre 35 et 40 %, et cette tendance est renforcée si le pouvoir calorifique est moins élevé;
. pour une valeur très élevée du coût de l'énergie de remplacement (15 $ du million de BTU), il semble qu'il y ait un avantage à augmenter la teneur en matières solides, c'est-à-dire, il y ait un maximum à ne pas dépasser. En réalité, ce maximum est déplacé vers la droite que par un faible écart, et il se situe autour de 42 à 43%, pour ce cas que l'on peut considérer "extrême" quant au prix que les compagnies papetières paient leur énergie. Dans la majeure partie des cas concrets, il semblerait donc que le niveau optimal à atteindre soit de 40%.

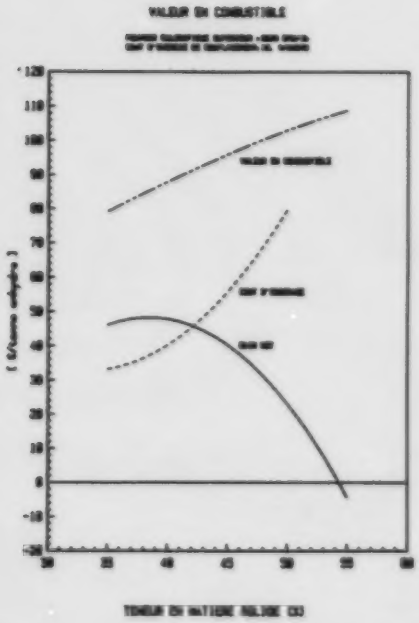

VALEUR EN COMBUSTIBLE
TENEUR EN MATIERE SOLIDE (%)

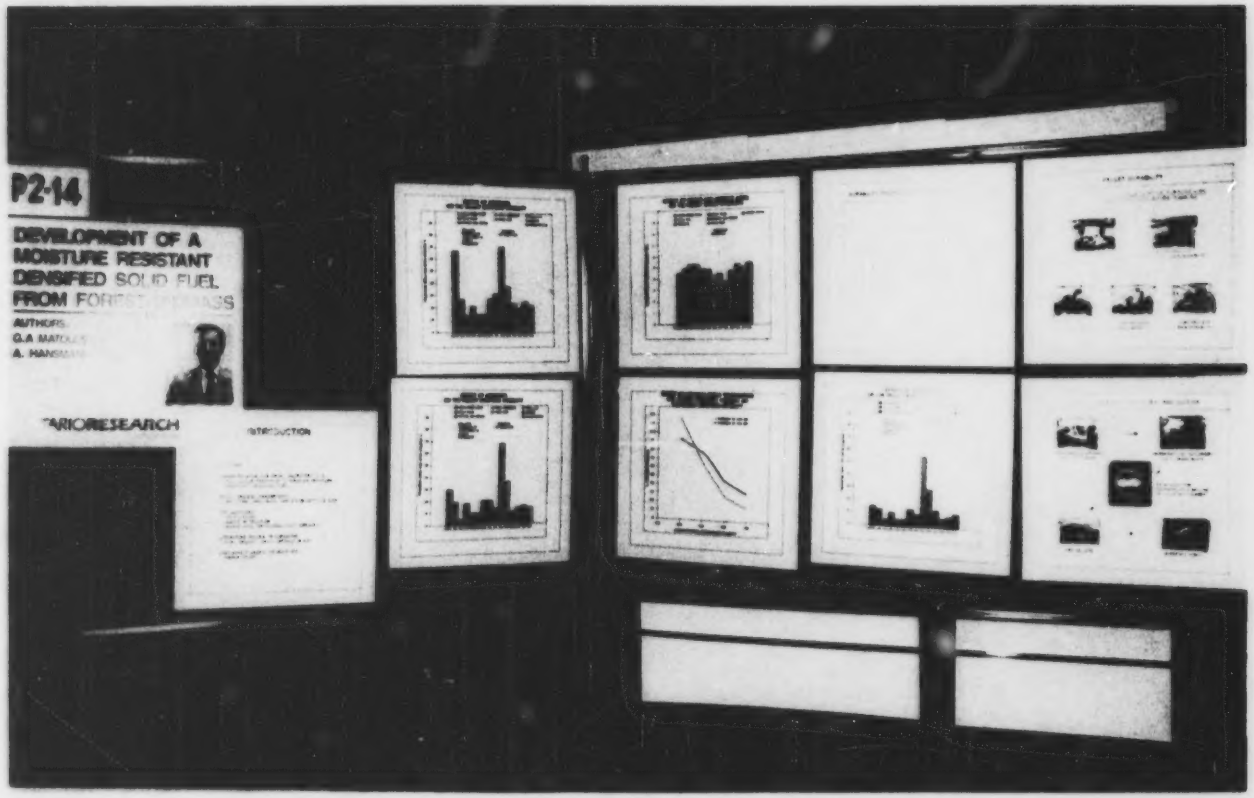

VALEUR EN COMBUSTIBLE
TENEUR EN MATIERE SOLIDE (%)


VALEUR EN COMBUSTIBLE
TENEUR EN MATIERE SOLIDE (%)


VALEUR EN COMBUSTIBLE
TENEUR EN MATIERE SOLIDE (%)


VALEUR EN COMBUSTIBLE
TENEUR EN MATIERE SOLIDE (%)


VALEUR EN COMBUSTIBLE
TENEUR EN MATIERE SOLIDE (%)


P2-14
DEVELOPMENT OF A
MOISTURE RESISTANT
DENSIFIED SOLID FUEL
FROM FOREST
AUTHORS
G.A MATOLES
A. HANSMAN
TARIORESEARCH
INTRODUCTION

COMMERCIAL WOOD PELLET PRODUCTION TRIALS WITH ADDITIVES FOR IMPROVED PRODUCTIVITY AND PELLET PERFORMANCE

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ORTECH International
Mississauga, Ontario

The work will transfer the findings of an earlier laboratory scale study to a full scale production unit and determine whether a stronger, more moisture resistant wood pellet can be economically produced on a commercial pellet mill by incorporating additives into the wood waste fuel. All work on this project will be carried out on a commercial pellet mill currently producing a wood fuel pellet. Thermocouple installations into the die and feed areas will measure the temperatures in key are as of the process. For process optimization, the main variables to be studied will be: temperature; feed moisture content; particle size distribution; ratio of bark to solid wood; and ratio of softwood. Four waste additives will be tried; polyolefin; tailings from corn oil or soybean oil production; pitch from oil refineries and tar from oil or coal processing.

Ces travaux permettront d'appliquer les résultats d'une étude antérieure réalisée en laboratoire à une installation de production à l'échelle commerciale et de déterminer s'il est possible de produire économiquement, dans une installation commerciale d'agglomération, des pellets de bois plus résistants aux chocs et à l'humidité, en ajoutant des additifs aux déchets de bois utilisés comme combustible.
Dans le cadre de ce projet, tous les travaux seront réalisés dans une installation commerciale d'agglomération servant actuellement à produire des pellets de bois destinés à être utilisés comme combustible. L'installation de thermocouples dans la matrice d'agglomération et au point d'introduction de la charge d'alimentation permettra de mesurer la température à des endroits clés du procédé. Voici les principales variables qu'il faudra étudier pour optimiser le procédé: température, teneur en humidité de la charge d'alimentation, distribution granulométrique des particules, rapport écore/bois massif et proportion de bois de conifère. Les quatre additifs qui seront étudiés sont le polyoléfine, les résidus obtenus au cours de la production d'huile de maïs ou d'huile de soja, le brai obtenu au cours du raffinage du pétrole et le goudron provenant de la transformation du pétrole ou du charbon.

INTRODUCTION

Our main objective in this study was to implement the laboratory findings of producing a moisture resistant densified biomass pellet on a commercial machine. In order to accomplish the main objective some of the variables in the pelletizing process, such as feed moisture content, operating temperature, production rate, feed wood species composition, steam or water addition rate were studied, in order to specify optimum manufacturing conditions.

A literature review of the emission from domestic and wood burning stoves is being compiled.

Addition levels of addatives selected were at such levels, that the economies of the wood pellet production are not unfavourably affected.

EXPERIMENTAL

Our work was carried out at a commercial unit owned by N.S. Bauman's Co. Ltd. in Wallenstein, Ontario. The Company uses hardwood sawdust and slabs from local sawmills to produce the pellets on a California pellet mill. The composition of the feed is variable as to species, bark content and moisture content.

The sawdust is mainly maple, occasionally contaminated with as much as 30% red oak. Bark content is variable between 10 - 30%. Moisture Content of the feed is generally 50 - 90%.

The incoming material is first rough hogged and then dried to about 15 - 20% moisture content in a 3 phase rotary suspension drier. The dried material is hammermilled and then screened to remove the fines before pelleting. The fines are

burned in the rotary kiln for energy generation.

The pelleting operation is controlled at Bauman's by the (1) feed conditioner dial setting (in the 4 - 7 unit range, usually at 6): (2) the amperage meter reading of the main drive for the pelleting mill and (3) the hand "feel" and look of the pellets. The pellets are normally at 6 - 12% moisture content out of the pelletizing unit and at specific gravity of~1.0g/cm^3.

After pelletization, the product is screened to remove fines and conditioned to a moisture of 8± 1% in the conditioning unit. The fines are returned into the feed bin of the pelletizing unit and remade into pellets. The finished product is bagged into 20 kg bags and sold to individual households for wood burning stoves. A part of the production is used to fire the boilers of some local greenhouses.

During a normal 12 hour production day, operating conditions and pellet quality change considerably. When starting at 7 a.m. the pelleting mill and the feed are cold at ambient temperature. With -in an hour of operation the die and feed areas of the pelleting mill heats up due to the friction and ompression forces of the pelleting operation. Steam is being driven off from the feed material, normally 4 - 6% MC is lost through the pelleting operation.

If the dried feed material falls below 12% MC, then moisture loss through the pelleting mill is too great to produce durable high strength proper size pellets. Generally at this point moisture is added to the conditioning unit to improve pellet quality, and raise the feed MC to the required 16 - 10% range.

Wood Species

We observed that fresh sawdust from green wood is the easiest to pelletize. Red oak has a deleterious effect on product quality and production rate Bark is beneficial in the pelleting. We have built a tumbling device to measure pellet quality (Fig. 3). The daily fluctuations of temperature in the pelleting operation are shown in Figures 1 and 2.

Steam Addition

In the conditioning unit of the pellet mill one can add, either water, or steam to adjust the temperature and or the moisture content.

Our measurement of production rate and fines generation indicated that steam addition is beneficial when steam is added less fines are generated and a more durable denser pellet is generated.

Temperature

Actual pelleting temperature can be varied by die temperature, the temperature of the feed material, and addition of steam to the conditioning unit. Unfortunately, at the production unit the simultaneous control of temperauture and moisture is next to impossible under current operating conditions.

We have been able to measure much better the temperatures than at the start of the project, but as soon as the feed temperature is raised by any of the previously mentioned routes the water evaporates at a faster rate from the wood and the pelleting operation does not necessarily improve. An on line moisture sensing device for the feed as well as the finished pellets would be the only way to take advantage of the improved pelleting performance at higher temperatures.

Currently when higher operating temperatures are being used, moisture drops to a level which is less than optimum. The operator adds cold water to the feed to raise moisture and the temperature of the whole unit drops immediately. The cycle is repeated several times a day.

Addatives

There are several problems in securing the proper type of addatives cost, availability, physical form size and shape to be competible with the pelleting operation and proper mixing with the wood feed.

Polyolefinic Waste

Throguh the "Ontario Waste Exchange" and the "Canadian Waste Materials Exchange" several sources of polyethylene and polypropelene were followed up. Films and trimmings of sheet materials have to be comminuted to mix properly with the wood meal. Several materials were found to be unsuitable waste from extrusion or injection mouldings that are in large chunks; threfore, unsuitable. Eventually we found a carpet manufacturer who produced the right shape and right size material. This material is available in large quantities but the price has not yet been agreed upon. The addition will be either through the feed bin, the fines chute, or the conditioning unit. Trials are currently under way.

Figures 1 to 4 illustrated on page 3.

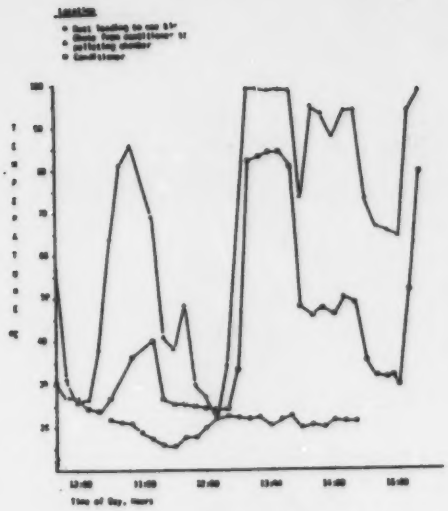


Figure 1: Operating temperatures Measured at Three Different Locations

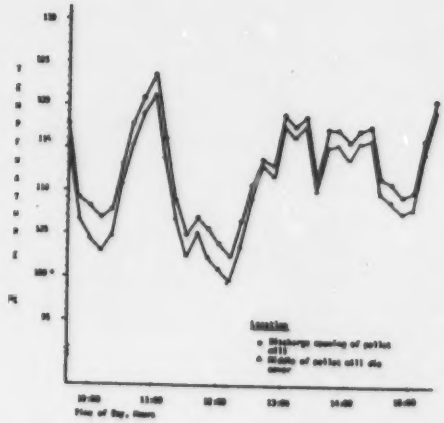


Figure 2: Operating Temperatures Measured at Two Different Locations of a Sprout-Bauer Pellet Mill

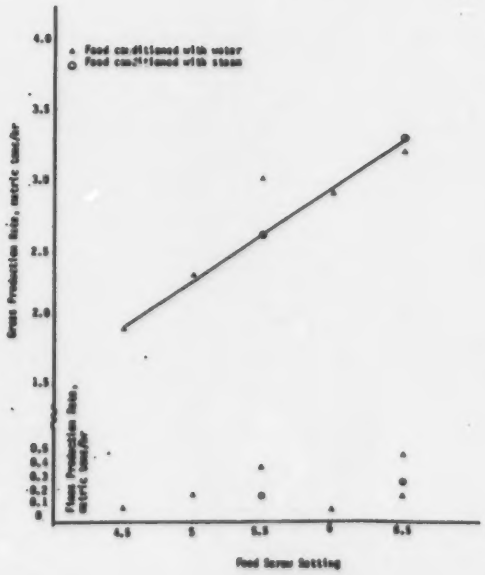


Figure 3: Gross Production Rate and Fines Production Rate vs. Feed Screw Setting

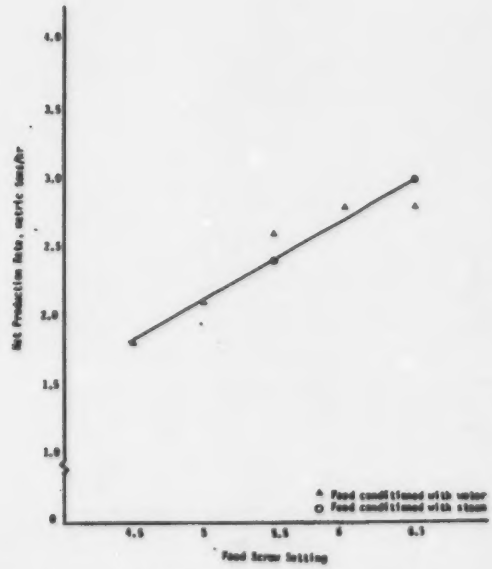
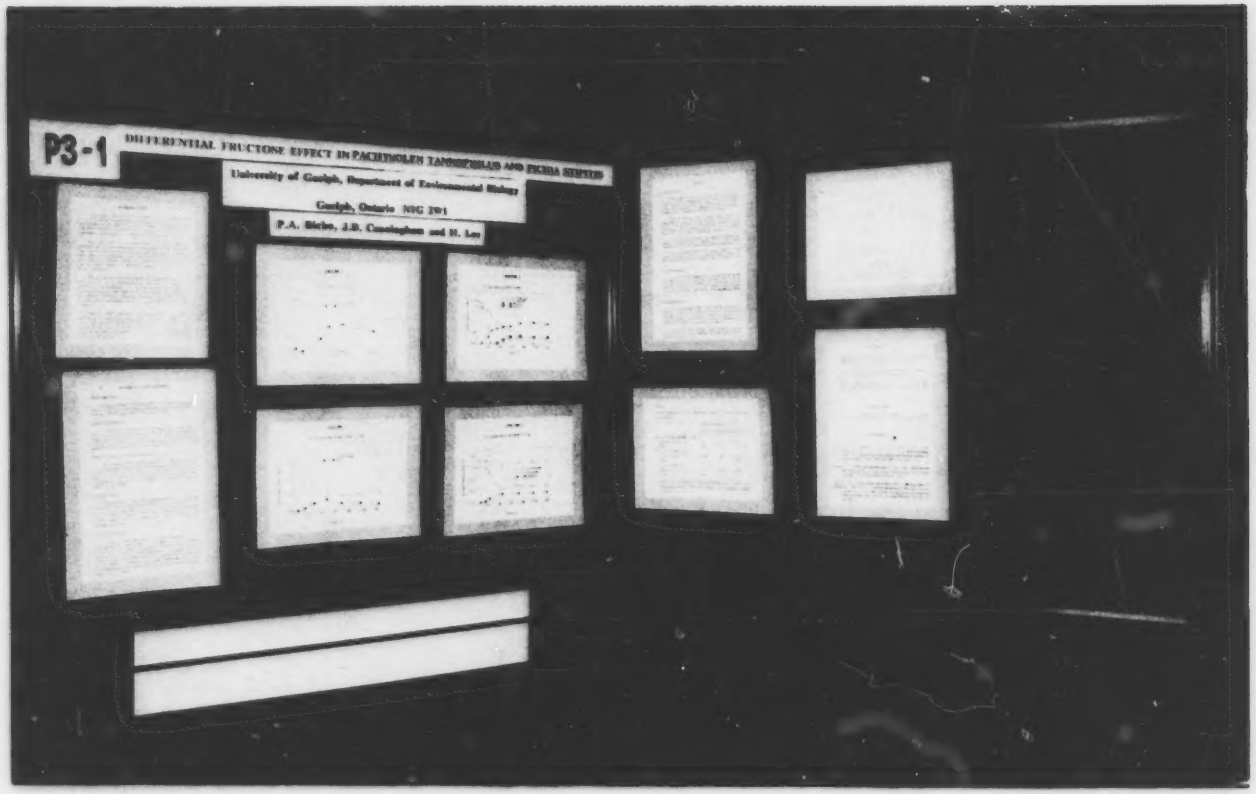


Figure 4: Net Production Rate vs. Feed Screw Setting


P3-1
DIFFERENTIAL FRUCTOSE EFFECT IN PACHYSOLEN TANNOPHILUS AND PICHIA STIPITIS
University of Guelph, Department of Environmental Biology
Guelph, Ontario N1G 2W1
P.A. Bicho, J.D. Cunningham and H. Lee

HEXOSE REGULATION OF D-XYLOSE UTILIZATION BY YEASTS

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Guelph, Ontario N1G 2W1

The utilization of D-xylose by yeasts is subject to regulation by induction and repression. Regulation has been demonstrated at the levels of D-xylose transport, xylose reductase and xylitol dehydrogenase. In recent studies, repression of xylose reductase and xylitol dehydrogenase activities by D-glucose, D-mannose and D-fructose was found to correlate with inhibition of D-xylose utilization in the yeasts Pachysolen tannophilus and Pichia stipitis. To enhance the prospect of D-xylose fermentation by yeasts, future strain improvement programs should select for strains which are not subject to glucose repression.

L'utilisation par les levures du D-xylose est sujete à la régulation par induction et répression. La régulation a été démontreé au niveau du transport du D-xylose, de la xylose réductase et de la xylitol déhydrogénase. Lors de récente études, la répression de l'activite de la xylose réductase et de la xylitol déhydrogénase par le D-glucose, D-mannose et D-xylose fut relieé a l'inhibition de l'utilisation du D-xylose par les levures Pachysolen tannophilus et Pichia stipitis. Afin d'augmenter la possibilité de fermentation du D-xylose par les levures, les programmes d'amelioration des souches futures devraient selectionner des souches non sujete à la répression par le glucose.

INTRODUCTION

Considerable research effort has been focussed recently on the bioconversion of lignocellulosic residues to ethanol. This is due mainly to an interest in converting an abundant and renewable resource to a liquid fuel which can then serve as a supplement or alternative to petroleum-based energy.

Lignocellulose is composed of cellulose, hemicellulose and lignin. Cellulose, a homogeneous polymer of D-glucose, is biodegradable, and its biological conversions are being investigated extensively as potential commercial processes. Lignin is a polyphenolic macromolecule whose potential has yet to be fully tapped. Hemicellulose is a polymer of pentoses (D-xylose, L-arabinose), hexoses (D-glucose, D-mannose, D-galactose) and acids (acetic and glucuronic acids) (Biely, 1985). The predominant hemicellulosic sugar is the aldopentose D-xylose which may comprise 20 to 40% of the total carbohydrates in biomass (Timell, 1964). Due to the abundance of D-xylose in lignocellulosic residues, its efficient utilization can significantly enhance the prospect of potential bioconversion schemes.

PROBLEMS ASSOCIATED WITH D-XYLOSE FERMENTATION

It is widely recognized that fermenting D-xylose is practicable only when it is performed in conjunction with the overall utilization of lignocellulose (Jeffries, 1985). It is, therefore, desirable that microorganisms used for the fermentation of biomass-derived carbohydrates should be able to convert a mixture of hexose and pentose sugars to ethanol. However, yeasts that ferment D-xylose efficiently in defined media generally perform poorly in acid hydrolysates of lignocellulosic materials. Several problems have been identified. A central problem is the presence of D-glucose in hydrolysates which can complicate D-xylose utilization (Hsiao et al., 1982). Many pentose-fermenting yeasts can convert D-glucose or D-xylose individually to ethanol. However, fermentation of pentoses in a glucose-xylose mixture does not proceed efficiently. This complication arises because fermentation of D-glucose precedes that of D-xylose, and the yeasts are not sufficiently tolerant of ethanol to complete the second fermentation. Another unique problem is the presence of hydrolysis-derived inhibitors which adversely affect microbial growth and fermentation (Tran & Chambers, 1985).

We are interested in studying the problems which limit the efficiency of pentose fermentation. Recently, we began to investigate the phenomenon of glucose repression in pentose-fermenting yeasts. Our approach is to elucidate the regulatory mechanism(s) involved in glucose repression. The objective is to understand the biochemical basis of this phenomenon, and then use the knowledge gained in future strain development programs.

INDUCTION OF D-XYLOSE METABOLISM

The control of D-xylose metabolism is believed to be exerted on parts of the D-xylose-specific pathway. D-

Xylose metabolism by yeasts begins with its transport across the cell membrane. Once inside, D-xylose is first reduced to xylitol by NADPH- or NADH-dependent xylose reductase. This is followed by oxidation of xylitol to D-xylulose by NAD-dependent xylitol dehydrogenase (Bolen & Detroy, 1985). D-Xylulose is then phosphorylated to D-xylulose-5-phosphate and metabolized via the pentose phosphate and Embden-Meyerhof pathways (Skoog & Hahn-Hagerdal, 1988).

The metabolism of D-xylose may be limited by its transport into the cells. Using nuclear magnetic resonance spectroscopy, the rate-limiting step of aerobic D-xylose metabolism in P. stipitis was shown to be D-xylose uptake. Under anaerobic conditions, the limiting step appeared to be at the level of xylitol dehydrogenase (Ligthelm et al., 1988).

Yeasts generally possess multiple uptake systems for D-xylose, some of which may transport sugars other than D-xylose. Rhodotorula glutinis possesses at least two carriers for D-xylose transport. The high affinity system was repressed in rapidly growing cells and derepressed by starvation (Alcorn & Griffin, 1978). In Candida shehatae, pre-growth on D-glucose or D-xylose produced a facilitated diffusion system that transports D-glucose (high affinity/low capacity), D-xylose (low affinity/high capacity) and D-mannose, but not D-galactose nor L-arabinose. However, cells derepressed by starvation formed different high affinity proton symports for D-glucose and D-xylose, respectively (Lucas & van Uden, 1986).

In P. stipitis, both low and high affinity proton symports for D-xylose operated simultaneously in starved or non-starved state (Kilian & van Uden, 1988). Pichia heedii also possesses two D-xylose uptake systems, one low affinity and one high affinity. When grown at a high D-xylose concentration (2%), activity of the low affinity system increased while that of the high affinity system decreased. When grown at a low D-xylose concentration (0.05%), the converse was observed (Does & Bisson, 1989).

Activities of enzymes in the D-xylose-specific pathway can be important in determining the metabolic flux. Studies on enzyme induction have focussed mostly on xylose reductase and xylitol dehydrogenase. Evidence for the importance of these enzymes in D-xylose metabolism was provided by genetic studies. Mutant strains of P. tannophilus which are deficient in xylitol dehydrogenase activity grew poorly on D-xylose or xylitol (Maleszka et al., 1983). Both activities can be induced by growth on D-xylose (Bicho et al., 1988; Bolen & Detroy, 1985; Ditzelmuller et al., 1984; Sugai & Veiga, 1988a). In P. tannophilus, activities can be induced by L-arabinose as well (Bolen & Detroy, 1985). Enzymes are poorly induced when cells are grown on D-glucose, D-fructose, D-mannose, D-galactose, mannitol, sorbitol or glycerol (Bicho et al., 1988, 1989; Bolen & Detroy, 1985; Sugai & Veiga, 1988a).

REPRESSION OF D-XYLOSE METABOLISM

Preferential utilization of D-glucose over D-xylose

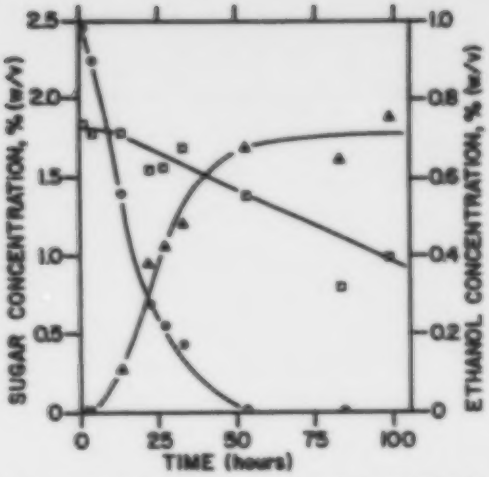

Fig. 1. Fermentation of a glucose-xylose mixture by P. stipitis NRRL Y7124. Symbols: (o) D-glucose; (□) D-xylose; (▲) ethanol. From Bicho et al. (1988). Reproduced with permission from American Society for Microbiology.

has been noted in cultures of Pachysolen tannophilus (Bicho et al., 1988; Detroy et al., 1982; Slininger & Bothast, 1988), Candida utilis (Hsiao et al., 1982), C. steatolytica (Panchal et al., 1988), Pichia heedii (Does & Bisson, 1989), and C. shehatae or P. stipitis (Bicho et al., 1988; Du Preez et al., 1986; Panchal et al., 1988). In most instances, diauxie results. An example for P. stipitis grown on a glucose-xylose mixture is shown in Figure 1. This phenomenon has been attributed to catabolite repression. In P. tannophilus, diauxie can be eliminated by using a large inoculum of cells pre-grown on D-xylose (Slininger & Bothast, 1988).

Catabolite repression is typically exerted by D-glucose or metabolically closely related carbon sources (Entian, 1986; Gancedo & Gancedo, 1986). However, repression of D-xylose utilization is not uniformly exerted by hexoses other than D-glucose. In P. tannophilus, D-mannose and D-fructose, but not D-galactose, can repress D-xylose consumption. In P. stipitis, D-mannose and D-galactose, but not D-fructose, inhibit D-xylose consumption (Bicho et al., 1988, 1989). Fermentation profiles of these two yeasts on a fructose-xylose mixture are shown in Figures 2 and 3. These results suggest that some basic regulatory aspects of D-galactose or D-fructose metabolism differed between the two yeasts.

Catabolite repression in pentose-fermenting yeasts has been attributed to inhibition by D-glucose of the transport and metabolism of D-xylose. In R. glutinis, 2-deoxyglucose competitively inhibited both high affinity and low affinity carriers. On the other hand, D-galactose competitively inhibited only the high affinity carrier (Alcorn & Griffin, 1978). In C. shehatae, the high affinity proton symport for D-xylose is reversible by either D-glucose or D-xylose. Therefore, it is unlikely to be of value during D-

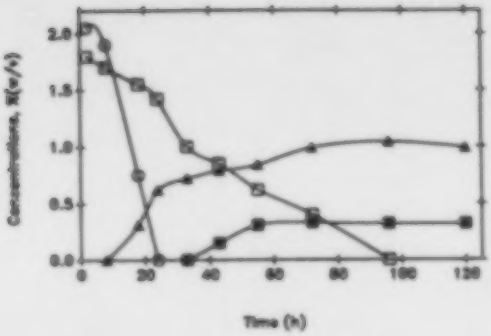

Fig. 2. Fermentation of a fructose-xylose mixture by P. tannophilus NRRL Y2460. Symbols: (o) D-fructose; (■) D-xylose; (▲) ethanol; (□) xylitol. Reproduced from Bicho et al. (1989).

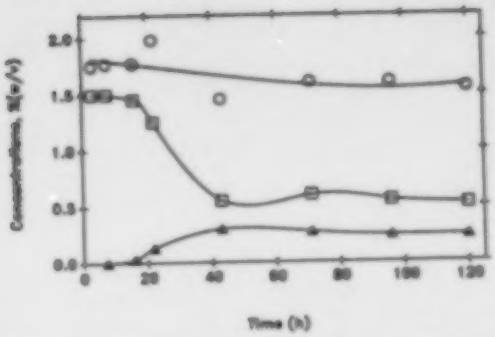

Fig. 3. Fermentation of a fructose-xylose mixture by P. stipitis NRRL Y7124. Symbols as in Fig. 2. Reproduced from Bicho et al. (1989).

xylose fermentation. However, the low affinity facilitated diffusion system for D-xylose is not affected by nutritional status nor by the presence of D-glucose or D-xylose (Lucas & van Uden, 1986). In P. stipitis, D-glucose competed with D-xylose for transport by the low affinity system and inhibited D-xylose transport by the high affinity system non-competitively (Kilian & van Uden, 1988). In P. hendii, D-glucose inhibited D-xylose uptake (Does & Bisson, 1989). These studies suggest that glucose inhibition by of D-xylose uptake can play a role in decreased consumption of the pentose.

Inhibition of D-xylose utilization may also result from repression of D-xylose-metabolizing enzymes. In P. tannophilus and P. stipitis, induction of xylose reductase and xylitol dehydrogenase activities can be inhibited by D-glucose, D-mannose, and 2-deoxyglucose. Cellobiose, L-arabinose, and D-galactose were not inhibitory (Bicho et al., 1988). D-Fructose inhibited enzyme induction in P. tannophilus but not in P. stipitis (Bicho et al., 1989). Therefore, for D-glucose, D-mannose and D-fructose, repression of enzyme induction is associated with preferential utilization of the hexose over the pentose in both yeasts (Table 1). The response of P. tannophilus to D-galactose also follows this pattern. However, the response of P. stipitis differed in that D-galactose was consumed ahead of D-xylose, though this hexose did not repress the induction of xylose reductase and xylitol dehydrogenase activities (Bicho et al., 1988).

In Pullularia pullulans, D-glucose can cause transient inhibition of the synthesis of xylitol dehydrogenase, and this effect may be reversed by exogenous addition of cyclic AMP (Sugai & Veiga, 1988b). On removal of the added D-glucose, a rapid and complete recovery of enzyme activity was observed. This transient enzyme inhibition by D-glucose was not prevented by cycloheximide, suggesting that active protein synthesis was not necessary for the effect. D-Glucose did not affect the in vivo stability of already synthesized xylitol dehydrogenase activity. This suggests that the glucose effect is not mediated by catabolite inactivation. Unfortunately, these authors did not study the effect of D-glucose on xylose reductase activity. In addition, mixed sugar utilization was not investigated. Therefore, it is not known what role(s), if any, might be played by xylose reductase and transiently-repressed xylitol dehydrogenase in D-xylose metabolism during glucose repression.

CONCLUDING REMARKS

The utilization of D-xylose by yeasts is a highly regulated event. The major regulatory mechanisms identified so far are induction and repression. Regulation has been demonstrated at the levels of D-xylose transport, xylose reductase and xylitol dehydrogenase. Lignocellulosic substrates of industrial interest generally contain several hexose sugars (D-glucose, D-mannose, D-galactose) which can repress D-xylose utilization. Therefore, hexose repression can limit the industrial potential of pentose fermentation. A sound understanding of the biological basis of hexose repression will be important in strain development programs aimed at eliminating this problem.

ACKNOWLEDGEMENTS

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Table 1. Summary of sequential sugar utilization and hexose inhibition of xylose reductase (XR) and xylitol dehydrogenase (XDH) activities in *Pachysolen tannophilus* NRRL Y2460 and *Pichia stipitis* NRRL Y7124.

Sugar mixtures	Sequence of Utilization		Inhibition of XR and XDH	
	Pa tan	*Pi st*	*Pa tan*	*Pi st*
D-glucose + D-xylose	G - X	G - X	Yes	Yes
D-mannose + D-xylose	M - X	M - X	Yes	Yes
D-galactose + D-xylose	X - Gal	Gal - X	No	No
D-fructose + D-xylose	F - X	X - F	Yes	No

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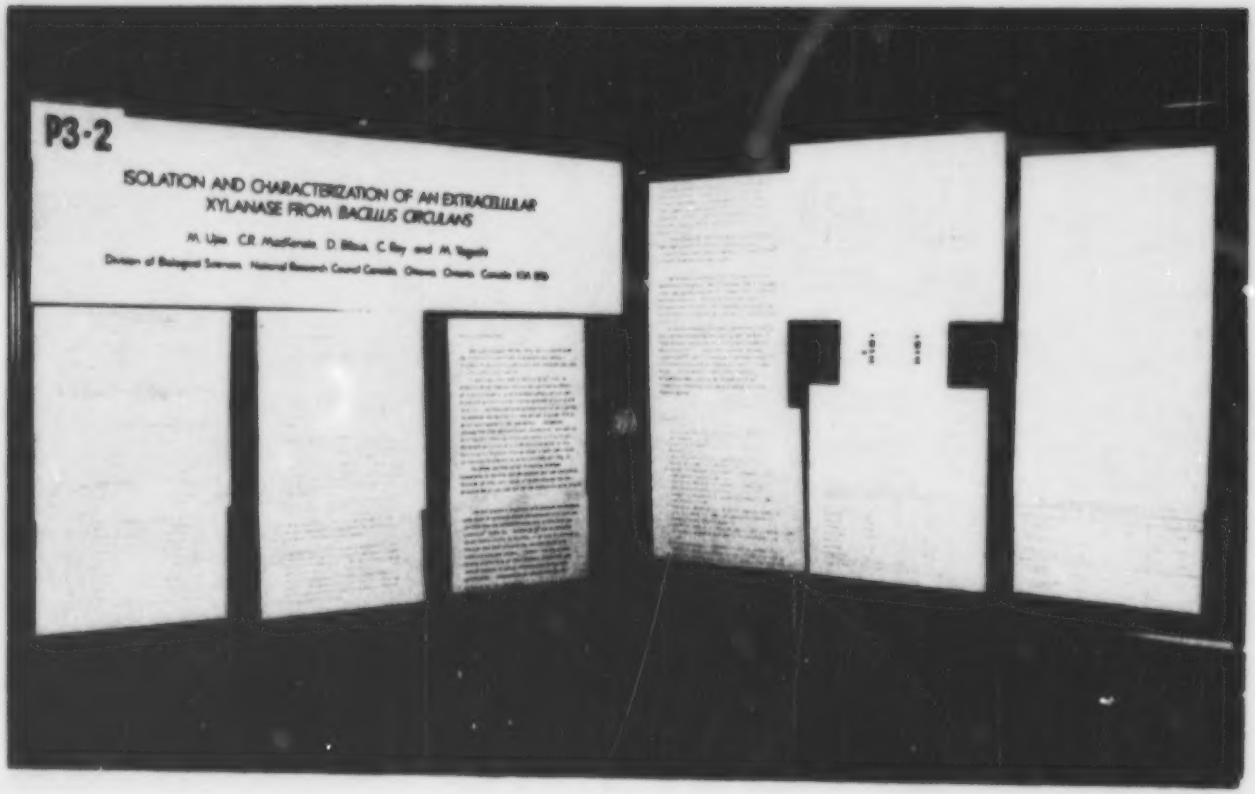
P3-2
ISOLATION AND CHARACTERIZATION OF AN EXTRACELLULAR XYLANASE FROM BACILLUS CIRCULANS
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ISOLATION AND CHARACTERIZATION OF AN EXTRACELLULAR XYLANASE FROM *BACILLUS CIRCULANS*

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A natural wild type xylanase was isolated from *Bacillus circulans* culture filtrates by CM Bio-gel A and DEAE Bio-gel A column chromatography and Toyopearl HW50S gel filtration. This enzyme had the same MW (22,000), pI(9.0), optimum pH(6.0) and temperature (53°C), pH stability (3.5-6.0), temperature stability (below 40°C), Km(1.5 mg/ml as larchwood xylan) and Vmax (103.70 µmol xylose/mg protein/min) as those of the wild type xylanase cloned and expressed in *E. coli*. The amino acid composition and N-terminal amino acid sequence of this enzyme were the same as those of *Bacillus circulans* xylanase and *Bacillus subtilis* xylanase which were cloned and expressed in *E. coli*.

Une xylanase naturelle de type sauvage a été isolée d'un filtrat de culture de *Bacillus circulans* par chromatographie sur CM Bio-gel A et sur DEAE Bio-gel A et par filtration sur gel HW50S de Toyopearl. Cette enzyme possédait la même masse moléculaire (22,000), le même pI (9,0), le même pH optimal (6,0), la même température optimale (53°C), le même stabilité de pH (3,5 - 6,0), la même température de stabilité (moins de 40°C), le même Km (1,5 mg/mL en xylane de mélèze) et le même Vmax (103,70 umol de xylose/mg de protéine/min) que la xylanase de type sauvage clonée et exprimée chez *E. coli*. La composition en acides aminés et la séquence des acides aminés déterminée à partir des extrémités N-terminales étaient les mêmes que la xylanase de *Bacillus circulans* et que la xylanase de *Bacillus subtilis* qui ont été clonées et exprimées chez *E. coli*.

INTRODUCTION

A 22k xylanase from *Bacillus circulans* has been cloned and expressed in *E. coli* by Yang *et al.*[1]. Esteban *et al.*[2] described a low molecular weight xylanase (15K by gel filtration) from *B. circulans* culture filtrate. We have been investigating the similarity among low molecular weight xylanases (around 20K to 22K) from bacteria and fungi, comparing the enzymatic properties of these xylanases, and studying the relationship of enzyme structure-function. Thus, we report here a comparison of sequence and enzyme characterization of *B. circulans* xylanase cloned in *E. coli*, and that isolated from the *B. circulans* culture filtrates. We conclude that two enzymes are the same functionally and structurally.

MATERIALS AND METHODS

Growth of microorganism. *Bacillus circulans* (NRC No. 9024) was grown in a medium containing 6.0 Na_2HPO_4, 3.0 KH_2PO_4, 0.5 g NaCl, 110 µl of 1 M $MgSO_4$, 0.1 µl of 1 M $CaCl_2$ 1% yeast extract, 2.5 g urea and 2g xylan per Litre cultures were incubated for 24h at 30°C, 200 rpm.

Chemicals. Xylan was obtained from Sigma Chemical Co. DEAE Bio-gel A and CM Bio-gel A were purchased from Bio-Rad Laboratories. Toyopearl HW50S was from Toyo Soda, Japan. All other chemicals were commercials products of analytical grade.

Enzyme assay method. Xylanase activity was assayed as follows. The reaction mixture contained 0.05 ml of enzyme solution, 0.2 ml of 0.1 M acetate buffer (pH 6.0) and 0.25 ml of 1% xylan solution. After incubation at 40°C for an appropriate period, the reducing sugar produced was measured by the method of Somogyi and Nelson. One unit of enzyme activity was defined as that amount of enzyme that produced one µmol of reducing sugar in one minute under the assay conditions.

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Analytical methods. Protein content was measured by the method of Bradford using Bio-Rad Protein Assay with bovine serum albumin as a standard. The absorbance at 280 nm was used for monitoring protein in column effluents. The amount of carbohydrate was measured by the phenol-sulfuric acid method with D-glucose as a standard.

Electrophoresis. Polyacrylamide gel electrophoresis and isoelectric focusing were performed by the standard method using a PhastSystem (Pharmacia) with 10-15% polyacrylamide gradient gels and pH 3-9 gels, respectively.

Amino acid composition and N-terminal sequence analysis. Amino acid composition analysis was done with a Durrum 500 Amino Acid Analyzer and N-terminal sequence was done with a Beckman Model 890 M Sequencer.

RESULTS AND DISCUSSION

Bacillus circulans (NRC No. 9024) was incubated under the conditions decribed in materials and methods. 10 Liters of the culture supernatant were collected and used for xylanase purification.

As previously described by Esteban *et al.*[3], the low molecular weight xylanase fraction was adsorbed on CM bio-gel A equilibrated in 10 mM phosphate buffer, pH 6.0, and eluted with a linear sodium chloride gradient of 0 to 0.5 M (Fig. 1). The fractions with xylanase activity were pooled, concentrated and applied to a DEAE Bio-gel A column (2.4 by 45 cm) equilibrated in the same buffer. Unadsorbed xylanase fractions were collected, concentrated, and applied to a Toyopearl HW50S gel filtration column (2.4 by 90 cm). The enzyme was eluted with 10 mM phosphate buffer pH 6.0, containing 0.1 M sodium chloride and showed a Ve/Vo ration which corresponded to a molecular weight of 7,000 ± 500.

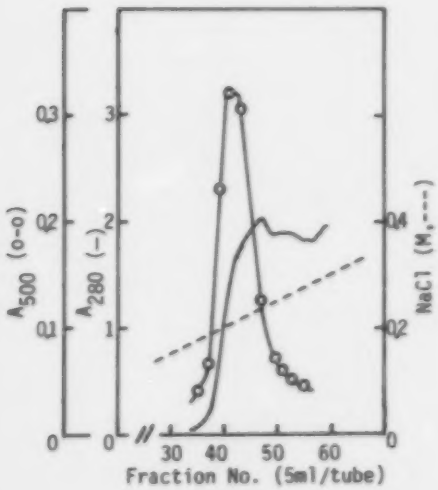


Fig. 1. CM Bio-Gel A Column Chromatography O-O; xylanase activity, -; protein, ---; NaCl (M).

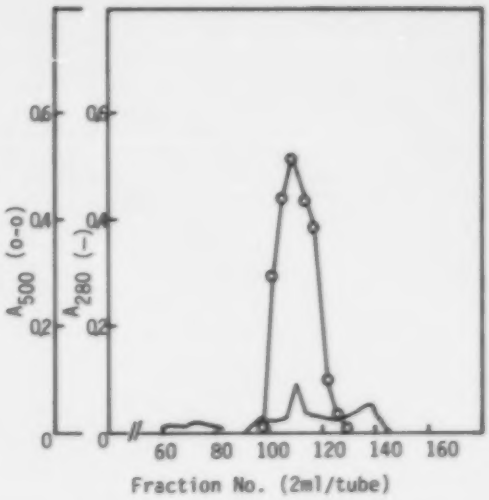
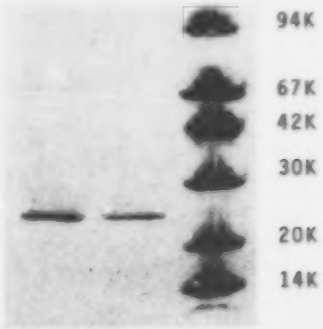


Fig. 2. Toyopearl HW50S Gel Filtration o-o; xylanase activity, -; protein.

The enzyme purified by gel filtration displayed homogeneity on SDS-PAGE (10-15% gradient gel) and isoelectric focusing (pH 3-9), with values of 22,000 obtained for the molecular weight (Fig. 3) and over 9.6 for the isoelectric point.



cloned purified

Fig. 3. SDS-PAGE.

Certain enzymatic properties were examined and compared with those of xylanases cloned and expressed in E. coli[11] and purified from the culture filtrate both in this work and previously[2] (Table 1).

Since Yang et al.[5] and Esteban et al.[2] identified and described two distinct xylanases from B. circulans, the culture filtrate must, therefore contain a second xylanase different from that which we isolated.

Table 1. Comparison of Xylanases from B. circulans

properties	xylanase B[2]	xylanase 22K**	cloned in E.coli**
Molecular weight (SDS-PAGE)	15,000*	22,000	22,000
pI	9.1	9.6	9.6
Sugar content (%)	ND	0	0
Optimum pH	5.5-7	6.0	6.0
Stable pH	ND	3.5-6.0	3.5-6.0
Optimum temp.(°C)	ND	53	53
Stable temp.(°C)	ND	below 40	below 40
Km(mg/ml)	4	1.58	1.50
Vmax(U/mg)	ND	103.70	108.00
Products from xylan	X_2,X_3,X_4	X_2,X_3	X_2,X_3

*, gel filtration; **, larchwood as substrate on the analyses.

Esteban et al.[2] did not do molecular weight determinations by SDS-PAGE and so we have no evidence to indicate that both xylanases are the same enzyme with identifical molecular weights. However, the two enzymes display similarities in their enzymatic properties, and show similar behavior in column chromatography during their purification. Consequently, we believe that the two xylanases are the same enzyme.

The enzymatic properties of the 22K xylanase from B. circulans, cloned and expressed in E. coli by Yang et al.[11], have been examined. As shown in Fig 3, each xylanase, cloned or purified, had the same mobility on SDS-PAGE. The two xylanases were also similar in most of their enzymatic properties (Table 1). Moreover, the N-terminal amino acid sequence suggests that the two xylanases are the same protein (Fig. 4).

(a),(b);

1 10
Ala-Ser-Thr-Asp-Tyr-Trp-Gln-Asn-Trp-Thr-

11 20
Asp-Gly-Gly-Gly-Ile-Val-Asn-Ala-Val-Asn-

21 30
Gly-Ser-Gly-Gly-Asn-Tyr-Ser-Val-Asn-Trp-

Fig. 4. Identical N-terminal Amino Acid Sequence of (a), B. circulans extracellular purified xylanase; (b), B. circulans cloned xylanase.

The amino acid sequences deduced from the nucleotide sequences of the genes of the 22K xylanases from B. circulans[1] and B. subtilis[3] show that the two xylanases have an identical amino acid sequence. Paice et al.[3] also describe that strong evidence for homology was found when the B. subtilis xylanase amino acid sequence was compared to a xylanase from B. pumilus[6].

We are now comparing the primary structures of the low molecular weight xylanases from fungi as well as bacteria[8]. These xylanases seem to be quite similar both structurally and functionally[7,8]. Two of these xylanases have been crystallized[9,10], and it is hoped that the three-dimensional structure of the enzymes will become available in the near future. In the current research field of protein engineering, these xylanases may provide unique and interesting information with regard to enzyme structure-function studies[7].

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P3-4

CELLULOSE-BINDING DOMAINS OF *CELLULOMONAS FIMI* CELLULASES

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Endoglucanase A (CenA) and an exoglucanase (Cex) of *Cellulomonas fimi* are glycoproteins which bind tightly to cellulose. The glycosyl groups are not required for the binding, which is mediated in each enzyme by a discrete cellulose-binding domain (CBD). Removal of the CBDs by proteolysis does not inactivate the enzymes. The CBDs bind to cellulose when joined to other proteins by gene fusion.

INTRODUCTION

The Gram positive bacterium *Cellulomonas fimi* can degrade microcrystalline cellulose. The complex enzyme system it secretes during growth on Avicel contains an endoglucanase (CenA) and an exoglucanase (Cex) which bind tightly to the substrate[1,2]. The binding facilitates purification of the enzymes[1,2]. Cloning of the genes, *cex* and *cen*A, for Cex and cenA, respectively, in *Escherichia coli* allows comparison of the glycosylated and non-glycosylated forms of the enzymes. Glycosylation does not affect the catalytic properties of the enzymes, their stabilities, or their binding to cellulose[2,4]. It does protect them from proteolysis when they are bound to cellulose, but not when they are in solution[4]. Cex and CenA comprise 443 and 418 amino acids, respectively[5,6]. Each enzyme contains a sequence of approximately 110 amino acids which is 50% conserved, situated at the N-terminus of CenA but at the C-terminus of Cex(Fig. 1)[7]. The conserved sequence is joined to the remainder of each enzyme by a sequence of 20 amino acids comprising only proline and threonine, the so-called Pro-Thr box (Fig. 2)[7]. The conserved sequences are the cellulose-binding domains (CBDs) of Cex and CenA, which, as shown here, function normally when joined to other proteins.

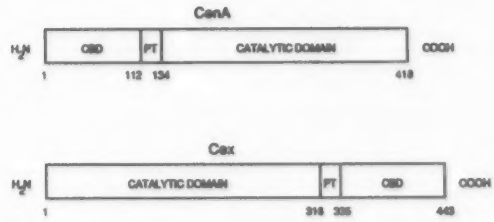

Figure 1. Overall structure of the endoglucanase (CenA) and exoglucanase (Cex) of *Cellulomonas fimi*. PT denotes the Pro-Thr box and CBD the cellulose-binding domain. Amino acids are numbered from the N-terminus of the processed enzyme.

```
      112                          134
CenA  PTPTPTPTTPTPTPTPTPTPTPTPTPT
Cex     PTPTPTTPTPTPT-TPTPTPT
      316                          335
```

Figure 2. The Pro-Thr boxes of CenA and Cex.

RESULTS

CenA and Cex comprise discrete catalytic and cellulose-binding domains.

CenA and Cex produced in *E. coli* are not glycosylated, and are referred to as ngCenA and ngCex, respectively. The native enzymes from *C. fimi* are glycosylated, and are referred to as gCenA and gCex, respectively.

ngCenA and ngCex bind to microcrystalline cellulose (Avicel). Each protein is cleaved into two major fragments by a *C. fimi* protease. The larger fragment from each protein, M_rs of 35 kDa for ngCex and 30kDa for ngCenA, is catalytically active but unable to bind to cellulose. The smaller fragment from each enzyme, M_rs of 8 kDa for Cex and 20 kDa for CenA, is catalytically inactive but can still bind to cellulose[9]. The site of cleavage in each protein is at the C-terminus of the Pro-Thr box (Fig. 3)[8].

Thus, CenA and Cex comprise discrete catalytic and substrate-binding domains which function independently of each other.

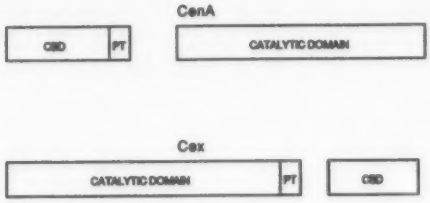

Figure 3. Cleavage of CenA and Cex by the *C. fimi* protease.

The catalytic domains of CenA and Cex function when fused to heterologous polypeptides.

The abilities of the catalytic domains and the CBDs of CenA and Cex to function when separated from each other by proteolysis suggested that the domains might also function when fused in-frame to other polypeptides.

The arrangements of the domains, with the CBD at the C-terminus of Cex but at the N-terminus of CenA, prompted the construction of a gene fusion which encodes a Cex-CenA hybrid polypeptide. The catalytic domain of Cex is at the N-terminus of the fusion polypeptide, separated from the catalytic domain of CenA by the Pro-Thr box and the first 32 amino acids of the CBD of Cex (Fig. 4)[9]. The fusion polypeptide has exoglucanase and endoglucanase activity (Table 1). Therefore, the catalytic domain of each enzyme functions when fused to a heterologous polypeptide.

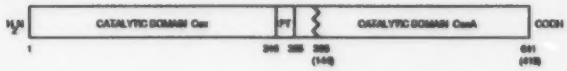

Figure 4. Structure of the Cex-CenA fusion polypeptide. The underlined number is the number of amino acids in the fusion protein; the numbers in parentheses are for the amino acids from CenA; the other numbers are for the amino acids from Cex. The fusion point is indicated by the jagged line.

Enzyme	Specific activity (units/mg protein) on	
	pNPC	CMC
Cex	90	700
CenA	nd	410
Cex-CenA fusion	10	150

Table 1. Activities of various proteins in *E. coli* JM83 extracts. pNPC is p-nitrophenylcellobioside; CMC is carboxymethylcellulose; nd means not detectable.

The CBDs of CenA and Cex function when fused to heterologous polypeptides.

The CBD of CenA (CBD_{CenA}) is at the N-terminus of the protein. TnphoA[10] was used to generate fusions of CBD_{CenA} to the N-terminus of alkaline phosphatase (PhoA)[11]. The fusion proteins obtained bind to cellulose only if an intact CBD_{CenA} is present (Fig. 5)[11]. As with ngCenA itself, those CBD_{CenA}-PhoA fusion proteins which bind can be purified to virtual homogeneity in a single step by binding to and elution from cellulose[11].

Figure 5. CBD_{CenA}-PhoA fusions. The sites of TnphoA insertion into the endoglucanase coding sequence are as indicated; (-) insertions do not bind to cellulose; (+) insertions bind to cellulose.

The CBD of Cex (CBD_{Cex}) is at the C-terminus of the protein. The coding sequence of the gene for a β-glucosidase (Abg) of an *Agrobacterium* sp.[12] was fused at its C-terminus to the sequence encoding CBD_{Cex}.

The Abg-CBD$_{Cex}$ fusion protein encoded by the gene fusion binds to cellulose, The binding is stable enough to allow continuous hydrolysis of p-nitrophenyl-β-D-glucoside (pNPG) by the immobilized Abg-CBD$_{Cex}$ without detectable desorption from the cellulose (Fig.6)[13].

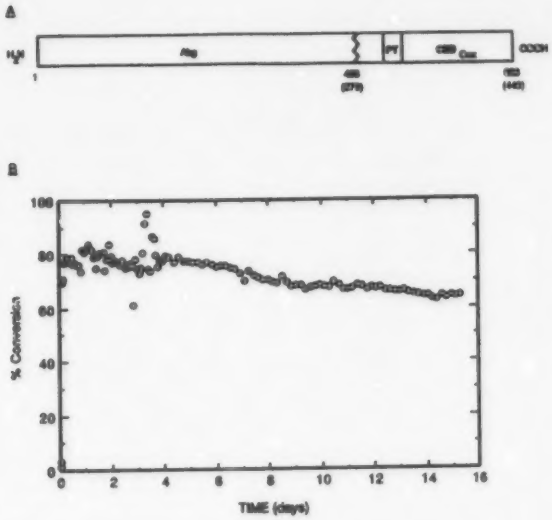

Figure 6. Abg-CBD$_{Cex}$ fusion. A. The underlined number is the number of amino acids in the fusion protein; the numbers in parentheses are for the amino acids from Cex; the other numbers are for Abg, which is 458 amino acids long. B. Continuous hydrolysis of pNPG by Abg-CBD$_{Cex}$ bound to cellulose. Substrate was passed through a column of immobilized enzyme and the product in the effluent measured by A_{400nm}.

DISCUSSION

The amino acid sequences of the CBDs of CenA and Cex are more than 50% conserved. Although the binding of the CBDs to cellulose is independent of the catalytic domains of the enzymes, the conservation suggests that the CBDs play some role in the degradation of cellulose. Experiments are in progress to define that role.

The general utility of the CBDs for the purification of fusion proteins and for immobilizing enzymes is obvious. We are developing vectors to facilitate their use in these areas.

We are attempting to define the sequences within the CBDs which are required for binding to cellulose. This may lead to the isolation or construction of mutants with increased affinity for cellulose.

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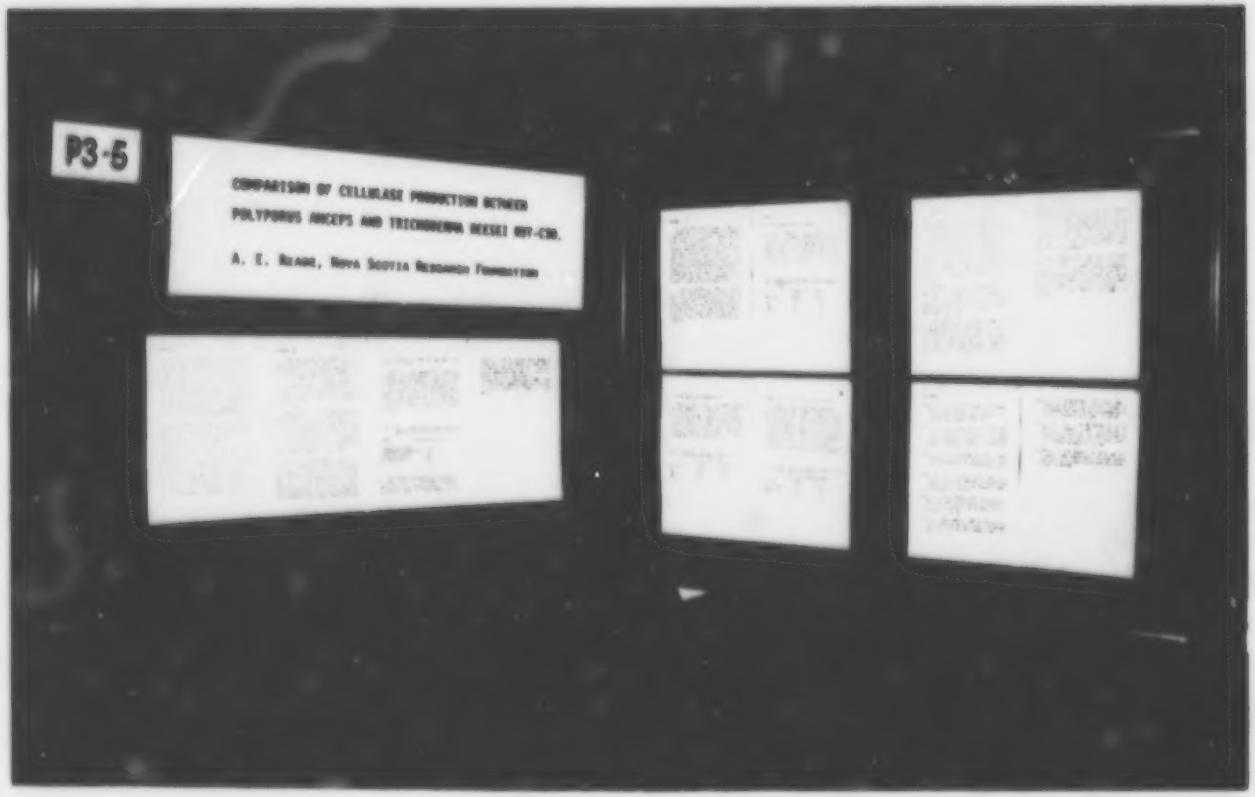
P3-5
COMPARISON OF CELLULASE PRODUCTION BETWEEN
POLYPORUS ANCEPS AND TRICHODERMA REESEI QM-CBH.
A. E. READE, NOVA SCOTIA RESEARCH FOUNDATION

COMPARISON OF CELLULASE PRODUCTION BETWEEN *POLYPORUS ANCEPS* AND *TRICHODERMA REESEI* RUT-C30.

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During solid-state fermentations of poplar shavings, the white rot fungus *P. anceps* generated high concentrations of reducing sugars in the fermenting biomass, compared to four other white rot fungi. This suggested that *P. anceps* might have potential as a commercial source of cellulase. Cellulase production by *P. anceps* was compared to that by *T. reesei* RUT-C30 in conventional submerged fermentation on pure cellulose and natural lignocellulose. The results indicated that yields of cellulase from *T. reesei* RUT - C30 were superior to those from *P. anceps* and that *P. anceps* did not have potential as a commercial source of cellulase in a conventional submerged fermentation.

Pendant la fermentation en milieu solide de copeaux de rabotage de peuplier, le champignon *P. anceps* produit des concentrations élevées de sucres réducteurs dans la biomasse en fermentation, en comparaison de quatre autres champignons. Ces grandes concentrations de sucres réducteurs laissent supposer que *P. anceps* pourrait être utilisé comme source commerciale de cellulase. On a comparé les quantités de cellulase produites par *P. anceps* et *T. reesei* RUT C-30 au cours de la fermentation submergée classique de cellulose pure et de lignocellulose naturelle. Selon les résultats, les rendements en cellulase obtenus avec *T. reesei* RUT C-30 étaient supérieurs à ceux obtenu avec *P. anceps*; de plus, *P. anceps* ne possède aucun potentiel comme source commerciale de cellulase par fermentation submergée classique.

INTRODUCTION

Concern over the practical availability of finite fossil fuel resources and a desire to use other, normally non-fuel related, resources more effectively has stimulated much research and development in the field of renewable energy resources. An important inclusion in the list of renewable resources is lignocellulosic biomass. In nature, vast quantities of lignocellulosics are degraded by the activities of a range of microorganisms which ultimately mineralize the biomass and make it available for the synthesis of new plant materials.

Among the early steps of the degradation process are delignification, and the hydrolysis of carbohydrate polymers, mainly cellulose and xylan, to the sugars glucose and xylose. These sugars can be used as the starting point for the biological synthesis of alcohols, which may be used for a variety of purposes including liquid fuels. The degradation of lignin and cellulose in nature is mediated by cellulolytic and ligninolytic enzymes found in fungi (Reese & Mandels, 1984; Kirk & Highley, 1973).

Considerable effort has gone into studies of cellulolytic fungi such as *T. reesei*. After mutation and fermentation optimization studies, this fungus has shown remarkable increases in the yield of cellulase and is one of the best known producers of cellulase (Brown *et al.*, 1987; Saddler *et al.*, 1983). Nonetheless, relatively few cellulolytic fungi have been examined in detail. A case can thus be made for further screening of fungi for cellulase producers and for the examination of fungi which are found to have cellulolytic potential.

During solid-state fermentations of poplar wood shavings, the lignin-degrading, white-rot fungus *Polyporus anceps* was observed to produce high levels of reducing sugars in the fermenting biomass relative to four other white-rot fungi under study (Reade & McQueen, 1983). After eight weeks incubation the reducing sugars rose from about 10% to almost 40% of the dry matter (Table 1). The poplar had not been pre-treated to increase its susceptibility to fungal degradation.

These observations suggested that this strain of *P. anceps* (F-784-S, U.S. Forest Products Laboratory, Madison, WI) would be worth examining as a possible candidate for commercial cellulase production. The possibility existed that cellulase from *P. anceps* was either highly active or produced in larger amounts than from the other fungi in the study. Although the initial observations were made in a solid-state fermentation system, it was decided, in

Table 1. Reducing sugars produced during solid-state fermentation of poplar shavings by five white-rot fungi.

Fungus	Reducing sugars (% d.m.)
Ganoderma applanatum	6.0
Phanerochaete chrysosporium	7.2
Fomitopsis ulmarius	12.0
Polyporus versicolor	13.4
Polyporus anceps	38.1

collaboration with the funding agency (EM&R), to use more conventional submerged fermentation techniques to evaluate P. anceps as a commercial cellulase producer.

METHODS

Cellulase production by P. anceps (F-784-S) and T. reesei RUT C-30 was compared in submerged fermentations using α-cellulose or ground (20 mesh) poplar wood as substrates. Various cellulase activities were monitored in the culture filtrates by measuring reducing sugars released from different carbohydrate substrates: filter paper (FP), Avicel, carboxymethylcellulose (CMC), salicin and xylan. Assay conditions were adjusted to achieve a linear relationship between enzyme concentration and reducing sugars released. Enzyme activities are expressed in International Units/mL of undiluted culture filtrate. One International Unit (IU) corresponds to one micromole of reducing sugar released per minute.

In addition, the practical hydrolytic potential of culture filtrates was assessed by incubating filter paper, Solka Floc or ground poplar with filtrates from the two fungi for 72 h and measuring the reducing sugars released. The substrate concentration was 100 mg/mL and the quantity of culture filtrate (T. reesei, 9 day culture; P. anceps, 14 day culture) added was adjusted to achieve a CMC activity to substrate ratio of 20 IU/g.

RESULTS

Cellulase production on α-cellulose

Table 2 summarizes the cellulase activities

Table 2. Comparison of maximum cellulase activities during growth on α-cellulose in submerged culture.

Substrate	Enzyme activity (IU/mL)	
	T. reesei	P. anceps
FP	1.6	0.4
Avicel	1.3	0.1
CMC	24.5	23.6
Salicin	0.4	0.4

observed in the submerged fermentations after 10-12 days of incubation. Filtrates from both fungi showed similar activities against CMC and salicin but T. reesei filtrates had considerably more activity against FP and Avicel. Soluble protein in the culture filtrates was similar for both fungi (2 mg/mL) as was mycelial nitrogen (0.07 mg/mL).

Cellulase production on ground poplar

Again, cellulolytic activity in P. anceps cultures was poor compared to T. reesei (Table 3). After 21 days incubation, activity against FP was scarcely detectable and CMC and xylanase activities were very low with P. anceps. In contrast, T. reesei filtrates contained substantially higher levels of all three enzyme activities. Fungal growth, assessed by microscopic examination, was abundant in T. reesei cultures and poor in P. anceps cultures.

Table 3. Comparison of maximum cellulase activities during growth on ground poplar in submerged culture.

Substrate	Enzyme activity (IU/mL)	
	T. reesei	P. anceps
FP	0.8	0.0
CMC	28.8	3.1
Xylan	11.2	1.6

Hydrolysis of cellulosics by culture filtrates

T. reesei filtrates hydrolysed each substrate to a greater degree than P. anceps filtrates (Table 4). With Solka Floc and poplar, T. reesei filtrates released approximately twice as much reducing sugar in 72 h as P. anceps filtrates. Time courses of the hydrolyses showed the typical rapid, initial release of reducing sugars followed by a continuous decline in the rate of release. The less refined substrates were more resistant to hydrolysis by filtrates of either fungus. About twice as much reducing sugar being released from FP as from Solka Floc or poplar.

Table 4. Hydrolysis of cellulosics by culture filtrates from T. reesei and P. anceps.

Substrate	Conversion to reducing sugar (%)	
	T. reesei	P. anceps
Filter paper	11.9	7.3
Solka Floc	6.1	3.6
Poplar	4.6	2.9

DISCUSSION

P. anceps culture filtrates accumulated less cellulolytic activity than T. reesei filtrates. Although CMC and salicin activities were similar when the two fungi were grown on α-cellulose, FP and Avicel activities were much lower with P. anceps. The difference did not appear to be attributable to growth limitations as both fungi secreted similar amounts of soluble protein into the medium and produced similar amounts of mycelial nitrogen. Growing the cultures on poplar, which might have given an advantage to the white-rot fungus P. anceps in fact widened the disparity between them. Here, however, microscopic observations suggested that P. anceps simply did not grow as well as T. reesei.

The maximum cellulase activities reported here are low relative to those found in other studies of T. reesei RUT C-30 (San Martin et al., 1986; Saddler et al., 1985). This can be attributed to the low substrate concentration used (10 g/L) which has been shown to limit cellulase yield (San Martin et al., 1986; Mandy et al., 1984).

A more practical test of a potential commercial cellulase than the initial reaction velocity used to determine enzyme activity is to conduct a hydrolysis with relatively high substrate, enzyme and product concentrations and with incubation over days rather than minutes. Under these conditions, T. reesei was also superior to P. anceps especially with less refined substrates. The percent hydrolysis of the substrates was disappointingly low in this experiment when compared to previously published data. Duff et al. (1986), for example, reported about 35% conversion of Solka Floc to reducing sugars after 70 h incubation with T. reesei filtrate which was about six times the conversion obtained here. This may result from variations in the ratios of cellulase components other than CMC activity which was used as the standard between the two experiments.

The data presented herein indicate that P. anceps P-784-S is inferior to T. reesei RUT C-30 in its cellulolytic capabilities when compared in submerged culture. It is possible that this method of comparison was unsuitable for P. anceps which may be better adapted to growth in a semi-solid environment and that a comparison using solid-state culture techniques might allow P. anceps to show more of its potential.

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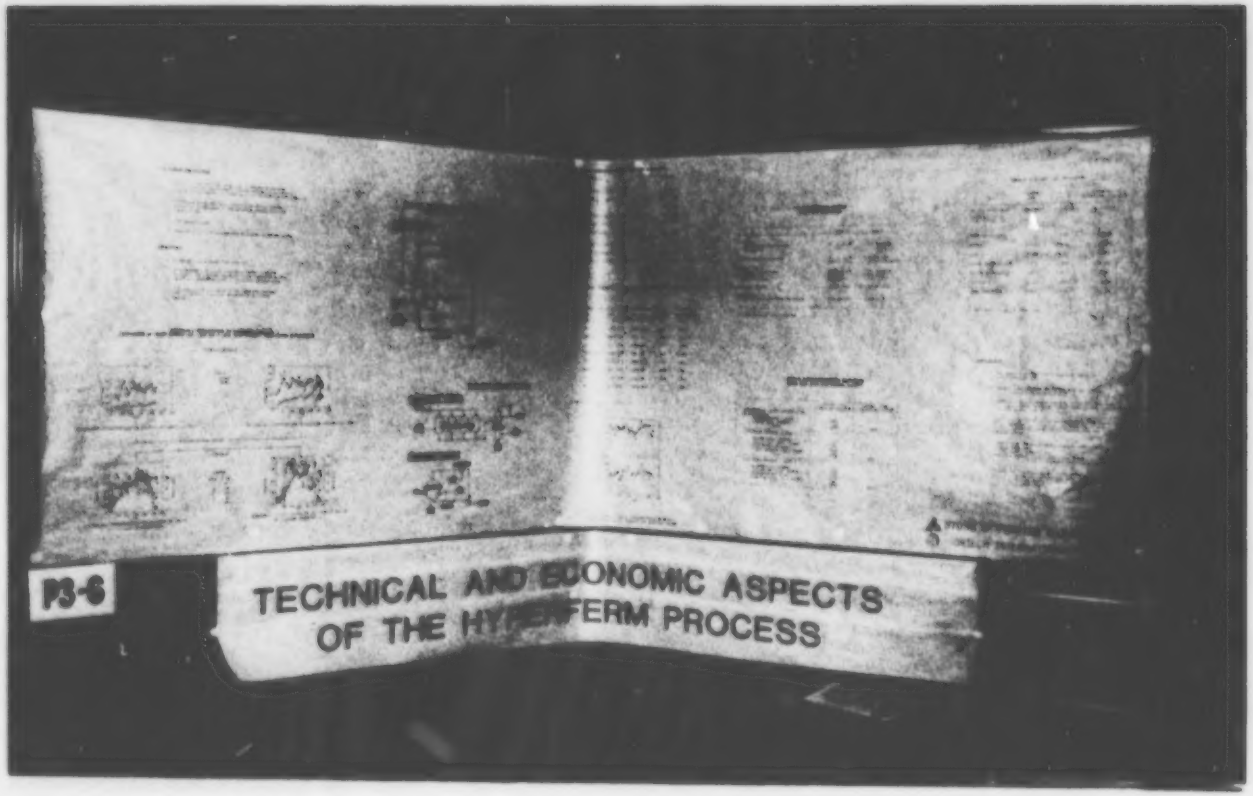
P3-6
TECHNICAL AND ECONOMIC ASPECTS
OF THE HYPERFERM PROCESS

TECHNICAL AND ECONOMIC ASPECTS OF THE HYPERFERM PROCESS

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This process for the continuous fermentation of glucose to ethanol with simultaneous recovery/removal of the product by vapour phase stripping has been evaluated at pilot scale. The technical and economic assessment will be presented. The potential for the commercialization of the technology will also be discussed.

An ongoing program to select or develop yeast strains able to ferment continuously at a temperature of 40°C or higher will be considered relative to its significance on the process development and economics.

On a évalué à l'échelle pilote ce procédé qui permet de produire de l'éthanol en continu par fermentation du glucose et récupération/élimination du produit par extraction en phase gazeuse. On présente une évaluation technique et économique. On examine aussi les possibilités de commercialisation de cette technologie.

On examine un programme en cours de réalisation dont le but est de choisir ou de développer de souches de levures capables d'assurer la fermentation en continu à une température de 40°C ou plus, en tenant compte de son importance sur la mise au point du procédé et sur ses aspects économiques.

INTRODUCTION

Economic analyses indicate that feedstock costs represent more than 60% of the total cost of the biological production of ethanol from renewable resources (e.g. corn or lignocellulosics). A producer must strive to guarantee long term profitability by maximizing by-product credits and minimizing the other production costs for pre-treatment and saccharification, fermentation, product recovery, dehydration and waste treatment. Markets for by-products are very sensitive to saturation and hence are not dependable for economic viability. This potential limitation reinforces the need for more efficient conversion technologies.

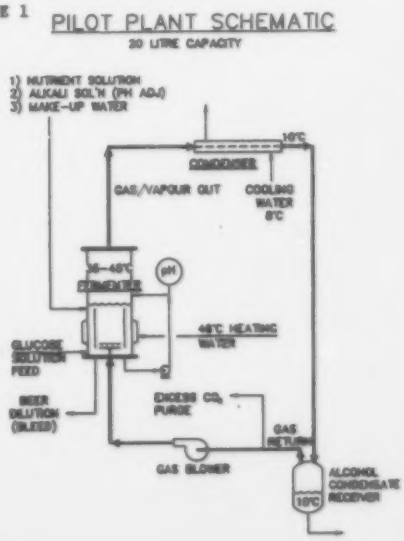
Unit operations of biological conversion technologies based on traditional processes (batch fermentation, distillation, etc.) have been refined to the extent that minor changes in one parameter may modify significantly the performance of other downstream process components. This emphasizes the need for an integrated approach in the development of more economical conversion technologies. It is the strategic thrust of the Hyperferm process.

The patented Hyperferm process involves the continuous fermentation of carbohydrates to ethanol coupled with the simultaneous removal/recovery of the volatile product by vapour-phase stripping. Inhibition of the fermentation by ethanol is thereby reduced and a continuous process is maintained. The efficiency of the process is enhanced by operation at elevated temperatures e.g. 35-49°C. The product of the process is a purified, concentrated ethanol solution - the condensate of the ethanol/water vapour entrained in the recycled gas stream. The ability to operate the process at bench-scale for extended periods has been demonstrated (Christison and Hayes, 1987). The results of pilot-scale tests are discussed in this report.

THE HYPERFERM PILOT-SCALE UNIT

The schematic of the Hyperferm pilot-scale unit is shown in Figure 1 and the operating criteria are listed in Table 1.

FIGURE 1



The feedstock, a commercial glucose syrup (DE-32, St. Lawrence Starch Co. Ltd.), was analyzed by HPLC to contain:

Glucose	- 26.3 ± 0.3%
Maltose	- 28.9 ± 0.7%
Oligosaccharides	- 26.3 ± 0.5%

The Saccharomyces cerevisiae, ATCC 24702, strain was selected for the pilot-scale tests following a screening of 23 candidate yeast species and strains which included batch and continuous fermentations at 35-45°C (Christison and Hayes, 1987). Individual performances were assessed against factors such as the apparent ethanol tolerance, the fermentation efficiency vs temperature and the level of by-product generation (particularly glycerol). This strain, which fermented glucose well, could not utilize maltose or oligosaccharides with sufficient speed to match the productivity of the system. Glucoamylase (Spiritanalase, SAN solution; Novo Corporation) added as required, hydrolyzed the maltose and oligosaccharides to glucose and prevented their accumulation in the broth.

In the bench-scale tests, the continuity of the fermentation could be maintained without cell recycle. At pilot scale, cell recycle had to be incorporated into the process to match the greater efficiency of the stripping/condensation system. Pilot-scale tests were performed over 4-5 months with the system operating continuously for periods of 20-60 days.

RESULTS

Typical data for the pilot-scale fermentation with ATCC 24702 are shown in Table 2. The range of ethanol concentrations in the broth (21.8 - 46.0 g/L) does not indicate higher or lower concentrations that may have occurred between sampling times. The daily maxima indicate the lack of ethanol tolerance in the yeast. The wide daily fluctuations reflect the cycle initiated when the ethanol concentration in the broth began to inhibit the fermentation. The ethanol removal by the vapour-phase stripping then continued until a lower threshold was reached where the active fermentation process was resumed.

The sensitivity to inhibition had significant impact on the operating efficiency of the process. The high productivities noted during the tests of 4.5 - 9.8g ethanol/L/h required that feedstock be added at a matching continuous rate. When inhibition occurred, the rate of addition of feedstock, if unchecked, quickly resulted in substrate concentrations in excess of 20% w/v. At this stage, the high glucose concentration and/or osmotic pressure was the major concern.

TABLE 1. OPERATING CRITERIA FOR PILOT-SCALE TESTS

Parameter	Range
Volume of Broth (Litres)	16-20
Temperature of Broth (°C)	34.4 - 36.2
pH	4.3 - 5.9
Biomass Concentration (g.d.w./L)	17.2 - 26.8
Gas Recycle Rate (Litres/min)	490 - 600
Gas Temperature - Condenser Inlet (°C)	34.0 - 34.5
- Condenser Exit (°C)	7.0 - 11.0
Condenser Coolant (°C)	7.0 - 10.0
Scrubber Temperature (°C)	10.5 - 11.0
Water Flow to Scrubber (Millilters/min)	8.0 - 15.0

If the rate of feedstock addition was reduced to match the decrease in the fermentation rate, it was likewise critical to respond rapidly when the active fermentation was restored. Otherwise, rapid depletion of the carbohydrate reserve occurred. The glucose concentration during the test period of 9 days was several times below detection limit. At such times, the productivity of the fermentation was below optimum and the risk of excessive foaming was high.

The mean volumetric productivity of the system was 9.2 g ethanol/L/hour based on the ethanol recovered in the condensate. If the ethanol lost in the broth during dilution was recovered, the productivity would increase to 10.8 g/L/hour. The range of ethanol concentrations in the condensates collected daily over the test period was only 123.5-165.2 g/L. The target concentration of 250g/L in the condensate will require that the ethanol concentration in the broth be maintained at 50-60 g/L at 35°C.

The tests confirmed that the process is capable of operation for long periods without contamination problems. The current tests used manual control of reagent addition and removal. In such a dynamic system, it is obviously preferable that automated control systems are introduced to ensure that the impact of ethanol toxicity and glucose saturation or depletion on performance is minimized.

ECONOMIC ANALYSIS

The economics of the Hyperferm process were compared with a conventional batch fermentation/distillation system for the production of approximately 92.4% w/w ethanol. The calculations

are based on the assumption that the Hyperferm technology will displace the beer column in the traditional approach (cf. Figure 2).

TABLE 2. TYPICAL MONITORING DATA FOR PILOT-SCALE FERMENTATION BY ATCC 24702

Day	Glucose(g/L) Max	Min	Glycerol(g/L) Max	Min	Ethanol(g/L) Max	Min	Biomass (g.d.w./L)	Ethanol in Condensate(g/L)
1	38.7	28.5	27.5	20.0	77.7	ND*	26.1	123.5
2	37.4	26.4	30.2	17.7	126.0	15.9	22.3	135.6
3	38.6	33.7	35.5	26.1	60.6	ND	25.4	154.4
4	42.1	30.4	41.1	30.4	82.9	28.2	21.3	165.2
5	37.6	24.5	37.8	25.3	68.7	ND	19.9	158.3
6	36.3	21.8	34.2	22.3	68.3	21.7	17.2	157.5
7	48.0	34.5	43.7	24.2	24.0	ND	26.6	146.7
8	41.0	38.2	33.2	28.4	32.8	ND	25.2	153.3
9	40.6	25.0	31.1	23.8	72.0	38.6		155.1

* ND = Not detected

TABLE 3. HYPERFERM PROCESS CASE I & II COMPARISON

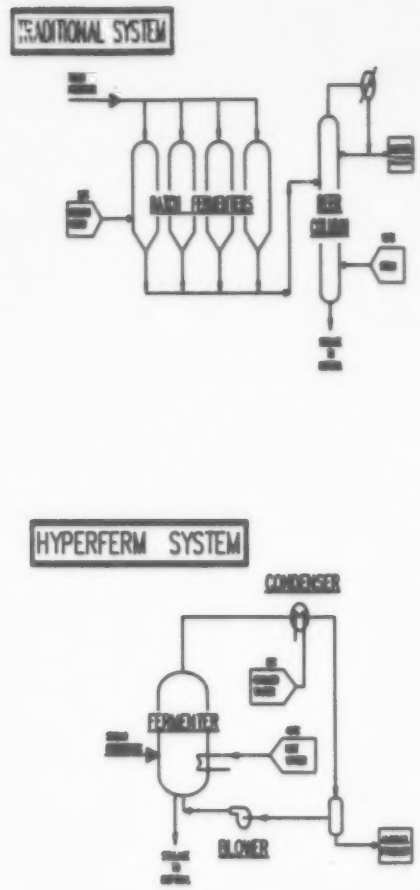
	Case I	Case II
Fermenter		
Broth Ethanol Concentration	3.3 weight %	6.0 weight %
Temperature	35°C	35°C
Gas Flow Rate to Fermenter	102,235 kg/hr 890,000 Litres	30,484 kg/hr 421,000 Litres/min
Alcohol Product		
Ethanol Concentration	10.7 weight %	15.1 weight %
Ethanol Rate	486 kg/hr	486 kg/hr
Total Flow Rate	4519 kg/hr	2537 kg/hr
Fermenter Volume	20,000 Litres	12,250 Litres
Productivity *		
Rate of Ethanol Produced per volume	24.3 gm/L/hr	40.4 gm/L/hr

5 million Litres per Year Production

The data from the pilot-scale tests did not meet the projected level of production based on a mean ethanol concentration in the broth of 6.0 % w/w at 35°C. However, the observed performance of the system at a mean ethanol concentration of 3.3% w/w in the broth matched well the projected data from a computer simulation model. Accordingly, the economic calculations were carried out for both the current production data (Case I) and the ultimate projected level of production (Case II). The comparative data for the two cases are shown in Table 3.

The economic calculations for a plant producing 5,000,000 liters of ethanol product per year indicate (Table 4) that the capital investment for the Hyperferm options would be lower than for the traditional fermentation/distillation system.

FIGURE 2 - Systems Comparison



At the current pilot-scale performance of the Hyperferm process (Case I), the operating costs of 15.3¢ per liter of ethanol are higher than for the traditional system at 12.4¢ per liter. However, the ultimate situation (Case II) indicates that the economics of production improve to the extent that the projected operating costs of 11.9¢ per liter are slightly less than the traditional system.

As calculated, energy consumption (utilities) represents the major cost element. The energy/utilities budgets for the respective process options are detailed in Table 5. The lower ethanol concentration (3.3% w/w for Case I) requires a much higher gas flow to recover the same amount of ethanol from the fermenter. The higher gas flow in turn is reflected in the higher fermenter heat input, higher cooling load, and higher blower capacity. By reducing the gas flow as in Case II, the energy requirements are lowered.

TABLE 4. ECONOMIC COST BREAKDOWN *

Item	Hyperferm Case I	Hyperferm Case II	Traditional Fermentation/Distillation
CAPITAL INVESTMENT	$2,600,000	$2,100,000	$3,000,000
OPERATING COSTS ($/Litre Ethanol)			
Chemicals & Adjuncts	0.0192	0.0192	0.0169
Utilities	0.0547	0.0298	0.0220
Labour	0.0287	0.0287	0.0287
Repairs & Maintenance	0.0118	0.0098	0.0134
Supplies & Miscellaneous	0.0015	0.0012	0.0010
Overhead	0.0371	0.0306	0.0423
TOTAL OPERATING COST	0.1530	0.1193	0.1242

* Plant size - 5,000,000 Litres/Year

The cost of energy as included in the above calculations is based solely on the measured energy requirements. A considerable portion of the energy requirements for the Hyperferm process is the low grade heat to maintain the operating temperature. When reductions in heat requirement are incorporated via the recovery of waste heat from other unit operations (e.g. distillation), the economic picture for the Hyperferm process is still more attractive. Energy savings also include the reduced energy consumption to maintain the feed to the scrubber at the desired temperature in winter months in colder regions. Another favourable difference for Case II is that with the higher ethanol concentration in the fermenter, the product ethanol concentration is increased to 19.1% w/w over the Case I concentration of 10.7% w/w. The higher product ethanol reduces the energy requirements for further upgrading processes.

The fermenter size for Case II can be smaller (12,000L vs. 20,000L) due to the lower gas flow rates and limitations in gas hold-up in the fermenter broth. The smaller fermenter size in Case II also contributes to higher projected productivity figures; 40.4 g ethanol/L/hour for Case II vs. 24.3 g ethanol/L/hour for Case I.

Waste treatment costs have not been included in the current economic evaluation. While the current data (dilution rates, biomass production) are not necessarily representative of the optimized process, projections indicate that the waste treatment costs for the Hyperferm will be less than for a conventional plant.

DEVELOPMENT OF THERMOTOLERANT YEAST STRAINS

The investigations undertaken to date emphasize the importance of ethanol and temperature tolerance of yeast strains for the optimization and economic viability of the Hyperferm process. Operation of the system at 40°C would allow more efficient removal of the ethanol coupled with more rapid fermentation.

A program is in progress to select a yeast strain able to function more efficiently in the Hyperferm process at this higher temperature. Yeast species or strains with demonstrated abilities to ferment and remain viable at 40°C have been selected from the John Labatt Culture Collection. The more promising strains from batch fermentation tests are being evaluated in the continuous Hyperferm process at bench scale at temperatures of 40-45°C. Protoplast fusion is also being investigated as a way to transfer desirable characteristics of temperature tolerance, ethanol tolerance or low by-product (glycerol) generation to candidate yeast strains lacking one or other of these requisites.

CONCLUSIONS

The mean productivity of the Hyperferm process has been increased to 9.2 g/L/hour using a commercial glucose syrup as feedstock. The process has still considerable scope for refinement. Further improvements are projected from the use of efficient cell recycle, higher operating temperature (40-43°C), the identification of more ethanol tolerant yeast strains, and the introduction of continuous monitoring techniques to control the glucose and ethanol concentrations so that steady state operation is attained.

Based on such improvements, the cost estimate to produce 92.4% w/w ethanol with the ultimate Hyperferm process, projected to be 11.9¢/L, compares favourably with the equivalent value of 12.4¢/L for a traditional fermentation and distillation route. When the potential cost savings from the efficient recovery of waste heat from unit operations such as distillation or the reduced energy consumption for cooling during the winter months in colder regions are considered, the economics appear still more attractive.

It is concluded that the Hyperferm process offers considerable promise as an alternative to traditional fermentation/distillation processes. With adequate control systems to match the dynamic nature of the process and more thermotolerant yeasts, this relatively uncomplicated technology will be easy to operate. The operating environment created by the elevated temperature and ethanol concentration is effective in minimizing the development of problems of contamination which plagues other continuous processes.

TABLE 5. ENERGY REQUIREMENT COMPARISON
BASIS: SMM LITRE/YEAR ETHANOL CAPACITY

	ENERGY INPUT [illegible]	COOLING LOAD [illegible]
CONVENTIONAL-BATCH FERMENTATION & DISTILLATION		
BEER RECTIFIER (STEAM)	3100	
PUMPS (ELEC. POWER)	[illegible]	
TOTAL	[illegible]	675
HYPERFERM PROCESS – CASE 1		
BLOWER (ELEC. POWER)	940	
CHILLER UNIT (ELEC. POWER)	1280	
FERMENTER HOT WATER	[illegible]	
PUMPS & EQUIP. (ELEC POWER)	[illegible]	
TOTAL	[illegible]	6810
HYPERFERM PROCESS – CASE 2		
BLOWER (ELEC. POWER)	470	
CHILLER UNIT (ELEC. POWER)	725	
FERMENTER HOT WATER	2270	
PUMPS & EQUIP. (ELEC POWER)	[illegible]	
TOTAL	[illegible]	3700

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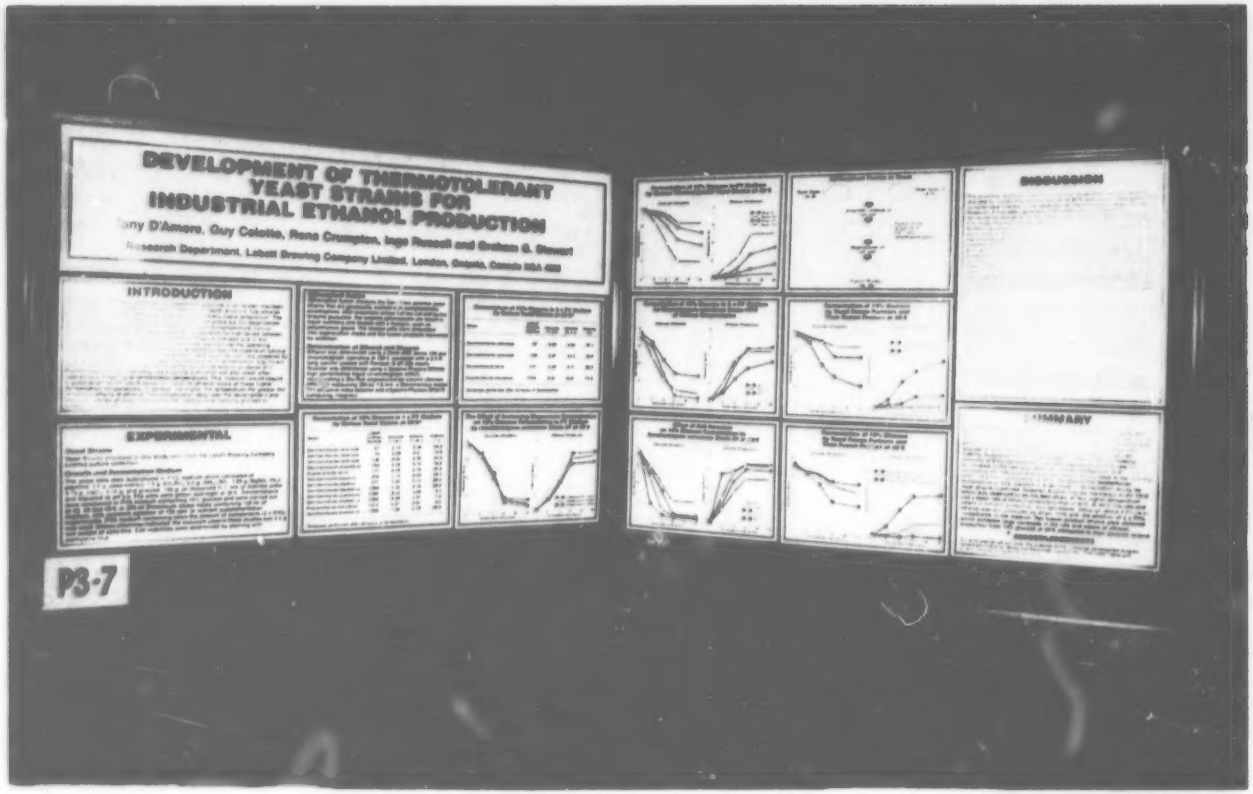
DEVELOPMENT OF THERMOTOLERANT
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Research Department, Labatt Brewing Company Limited, London, Ontario, Canada N5A 4B9
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DEVELOPMENT OF THERMOTOLERANT YEAST STRAINS FOR INDUSTRIAL ETHANOL PRODUCTION

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The use of fermentation ethanol as a liquid fuel has been increasing in many parts of the world. Significant cost savings in ethanol production and recovery would be expected if the fermentations were performed at 40°C or above. This, however, would require a yeast strain which could produce maximum ethanol levels at these higher temperatures. In order to isolate thermotolerant yeast strains, a number of yeast strains from various genera were screened for their ability to grow and ferment glucose to ethanol at 40°C. In general, fermentations at this and higher temperatures resulted in a decrease in the rate and extent of glucose utilization and ethanol production. However, the detrimental effect of performing high temperature fermentations could be overcome, to some extent, by increasing the nutrient components in the medium. In addition, increasing the cell density also resulted in an increase in ethanol production at these higher temperatures. The spheroplast fusion technique has been employed to genetically manipulate ethanol and temperature tolerant yeast strains in order to improve their ability to grow and ferment glucose at 40°C and above.

Partout dans le monde, on utilise de plus en plus comme combustible liquide l'éthanol obtenu par fermentation. On pense qu'il serait possible de faire d'importantes économies si les fermentations pouvaient être effectuées à une température égale ou superieure à 40°C. Cependant, il faudrait utiliser une souche de levure pouvant produire une quantité maximale d'éthanol en présence de température élevée. Pour isoler les souches de levures thermotolérantes, on a trié un certain nombre de souches de levures de genres différents de maniére à trouver celles qui peuvent croître et fermenter à une température de 40°C. En général, les fermentations réalisées à une température égale ou supérieure à 40°C se caractérisaient par une diminution de la vitesse et de l'ampleur de l'utilisation du glucose et de la production d'éthanol. Toutefois, l'effet néfaste de la température élevée pourrait être surmonté, dans une certaine mesure, si l'on augmentait la concentration des éléments nutritifs dans le milieu. En outre, l'augmentation de la densité de cellules s'est traduite également par une augmentation de la production d'éthanol aux températures plus élevées. On a utilisé la technique de fusion des sphéroplastes pour effecture des manipulations génétiques sur des souches de levure tolérantes à l'égard de l'éthanol et de la température, afin d'améliorer la capacité de ces levures à croître et à fermenter le glucose à une température égale ou supérieure à 40°C.

INTRODUCTION

The use of ethanol as a liquid fuel, as a blend with gasoline or on its own, has been increasing in many parts of the world. However, in North America, fuel ethanol production is generally not considered an economically viable proposition (1). The major factors contributing to the unfavourable economics are the dependence on corn and by-product prices and the requirement for temperature control. Typical yeast fermentations require that the temperature be maintained between 30 to 35°C to maximize ethanol production. In tropical climates and during the summer months in many non-tropical countries, maintaining the operating temperatures at the optimum fermentation temperature requires expensive cooling systems. In addition, many of the substrates employed (such as corn) are prepared by heating to high temperatures followed by cooling prior to fermentation. Significant cost savings become apparent if the fermentor can be kept at or above 40°C. Furthermore, ethanol recovery costs during distillation are also lower when operating at these higher fermentation temperatures (2). This, however, would require a yeast strain which could produce maximum ethanol levels at these higher temperatures. In general, the higher the temperature the greater the inhibitory effects of ethanol (3-7).

There are a limited number of reports on the selection of yeasts able

to grow and ferment at or above 40°C (2,7-10). *Kluyveromyces* strains were found to be more thermotolerant than *Saccharomyces* and *Candida* strains (9). However, *Kluyveromyces* and *Candida* strains are not as ethanol tolerant as *Saccharomyces* strains (2,8,9). In this manuscript, the selection and development of yeast strains suitable for fermentation at 40°C and above is reported.

MATERIALS AND METHODS

Yeast Strains

Yeast strains employed in this study were from the Labatt Culture Collection.

Growth and Fermentation Medium

The yeast cells were subcultured in PYG medium which consisted of: peptone, 3.5 g; yeast extract, 1.5 g; KH_2PO_4, 3.0 g; $(NH_4)_2SO_4$, 1.85 g; $MgSO_4.7H_2O$, 0.75 g; $CaCl_2$, 0.06 g; and glucose, 100 g; all dissolved in 1 litre of distilled water and adjusted to pH 5.6. The cells were grown overnight at 30°C. Fermentations were conducted in PYG medium containing 15% glucose and were carried out at 40, 43 and 45°C in 300 ml Erlenmeyer shake flasks containing 100 ml of medium, with constant agitation of 150 rpm. Unless otherwise indicated, the inoculum employed in these studies was 3.5 g wet weight of cells/litre. Cell viabilities were determined by staining with methylene blue.

Spheroplast Fusion

The spheroplast fusion technique was performed as described previously (11). Yeast strains, with appropriate selection markers, were grown in PYG medium containing 15% glucose for 18 h at 21°C with shaking. The cells were harvested by centrifugation at 4,000 x g for 10 min and washed once with sterile distilled water. Approximately 1 x 10^8 cells of each strain were suspended in 10 ml of dithiothreitol (DTT) buffer (25 mM EDTA, 1.2 M sorbitol, pH 8.0 and 50 mM DTT) and incubated at 27°C with shaking for 10 min. Cells were then washed twice with 1.2 M sorbitol and resuspended in 10 ml of lytic enzyme buffer (1.2 M sorbitol, 50 mM DTT and 0.01% glusulase (DuPont Pharmaceuticals) until approximately 80% of the cells were spheroplasted as assessed by microscopic examination. Cells were then washed three times with 1.2 M sorbitol, resuspended in 1.0 ml of sorbitol-$CaCl_2$ buffer (10 mM $CaCl_2$, 1.2 M sorbitol, pH 8.0) and divided into 0.5 ml aliquots. One aliquot was retained as a control and the other aliquot mixed with the fusion partner. After 10 min incubation, 1.0 ml of 40% polyethylene glycol was added and the strains were incubated for a further 30 min with gentle shaking. Cells were centrifuged at 2,000 x g for 10 min and resuspended in 5.0 ml of sorbitol-$CaCl_2$ buffer and embedded in selection agar and control agar (PYG) containing 1.2 M sorbitol and incubated at 37°C. After 7-10 days, the plates were examined for growth and fusion products selected.

Determination of Ethanol and Glucose

Ethanol was determined using a Carle AGC series 100 gas chromatograph operating at 180°C equipped with a 2.4 m long column packed with Poropak Q (81,000 mesh). Glucose was determined using a Spectra-Physics SP8100 high performance liquid chromatograph (HPLC) incorporating a Bio-Rad oligosaccharide column (Aminex HPX-42A) measuring 300 by 7.8 mm, a Micromeritics model 771 refractive index detector and a Spectra-Physics SP4270 computing integrator.

RESULTS AND DISCUSSION

This laboratory has recently screened approximately 70 yeast strains for growth ability at 40°C on PYG-agar plates containing 10% glucose (7). At this temperature, only 12 yeast strains were observed to have good growth ability. Table 1 lists these yeast strains and shows the results of the fermentation of 15% glucose at 40°C after 24 h. Table 2 lists four of these yeast strains and the results of the fermentation of 15% glucose in 2 X PYG medium at 40°C. It can be seen that under these conditions of increased nutrient addition, higher ethanol levels are produced when compared to the results in Table 1. In support of this, nutrient supplementation also results in an overall decrease in the glucose concentration in the medium at the end of fermentation when compared to normal growth conditions. These results clearly show that *Saccharomyces cerevisiae* strain 67 and *Kluyveromyces marxianus* strain 1510 are the most promising strains for high temperature fermentation, producing the maximum amounts of ethanol and utilizing virtually all of the available glucose after 24 h of fermentation at 40°C. It should be noted from the results in Tables 1 and 2 that although *Saccharomyces cerevisiae* strain 67 has relatively good cell viability at 24 h of fermentation, *Kluyveromyces marxianus* strain 1510 has the disadvantage of possessing very low cell viability. These two strains were used for the majority of subsequent studies.

As discussed above, increased nutrient addition to the medium results in the production of higher ethanol

Table 1. Fermentation of 15% Glucose in 1 X PYG Medium By Various Yeast Strains at 40°C[a]

Strain	Labatt Culture Number	Glucose (% w/v)	Ethanol (% w/v)	Viability (%)
S. cerevisiae	67	2.73	5.52	64.9
S. cerevisiae	70	5.09	4.51	14.9
S. cerevisiae	130	8.50	2.30	25.5
S. diastaticus	164	4.56	4.72	16.6
K. lactis	177	8.56	2.16	95.2
S. bayanus	276	5.14	4.53	43.3
S. bayanus	277	3.39	5.13	80.5
S. diastaticus	1384	5.32	4.10	83.8
S. diastaticus	1392	6.12	3.59	9.3
S. diastaticus	1393	6.59	3.47	7.8
K. marxianus	1510	5.47	4.01	4.3
S. diastaticus	1580	7.48	2.79	90.9

[a]Analyses performed after 24 hours of fermentation.

Table 2. Fermentation of 15% Glucose in 2 X PYG Medium By Various Yeast Strains at 40°C[a]

Strain	Labatt Culture Number	Glucose (% w/v)	Ethanol (% w/v)	Viability (%)
S. cerevisiae	67	0.68	6.24	57.1
S. cerevisiae	130	3.87	4.63	35.0
K. lactis	177	3.48	4.71	90.3
K. marxianus	1510	0.61	6.21	14.4

[a]Analyses performed after 24 hours of fermentation.

levels. It has been recently demonstrated that nutrient supplementation will increase ethanol production levels, especially under conditions of high substrate concentration (12). Figure 1 indicates that increasing the magnesium concentration in PYG medium also enhances the production of ethanol from 15% glucose at 40°C by *Saccharomyces cerevisiae* strain 67. It can be observed that there is approximately a 1% (w/v) increase in final ethanol yields with increasing magnesium concentration. Magnesium has been recently identified as playing a key role in increasing the ethanol tolerance of yeast (12,13). The beneficial effect of magnesium addition has also been observed in other yeast strains (data not shown) and probably results from the fact that some of the glycolytic enzymes involved in fermentation have a requirement for this cation.

The effect of increasing the fermentation temperature above 40°C on the utilization of 15% glucose is illustrated in Figure 2. Increasing the fermentation temperature to 43°C resulted in a decrease in the rate and extent of ethanol production, as well as a decrease in cell viability, for most of the strains examined when compared to the results in Table 1. For example, at 40°C

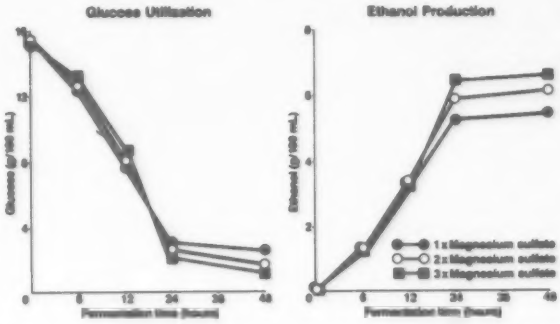

Figure 1. The effect of increasing magnesium concentration on 15% glucose fermentation by *Saccharomyces cerevisiae* strain 67 at 40°C.

Saccharomyces cerevisiae strain 67 produced approximately 5.5% (w/v) ethanol from 15% glucose, whereas approximately 3.4% (w/v) ethanol was produced at 43°C. *Saccharomyces diastaticus* strain 164 and *Saccharomyces bayanus* strain 277 were considerably affected at the higher fermentation temperature, producing only 0.5% and 1.5% (w/v) ethanol, respectively. On the other hand, *Kluyveromyces marxianus* strain 1510 exhibited no appreciable difference in the fermentation of 15% glucose at 43°C when compared to the results at 40°C. In fact, as illustrated in Figure 3, the rate of ethanol production is slightly greater at 43°C than at 40°C, with the production of approximately 6.0% (w/v) ethanol at both temperatures. At 45°C, there is a significant decrease in the rate and extent of ethanol production with this strain, although 4.5% (w/v) ethanol was produced after 48 h. Thus, *Kluyveromyces marxianus* strain 1510 may be beneficial for use in fermentations approaching 45°C. However, this strain has the disadvantage of possessing low cell viability after fermentation. This low cell viability is probably related to the inability of the strain to tolerate ethanol concentrations greater than 5% (w/v) (2,8,9).

The results discussed thus far have all been obtained employing 0.35% (w/v) cell inoculum. It has previously been reported that increasing the inoculum size or cell concentration decreases the severity of ethanol inhibition (14). The effect of increasing inoculum size on

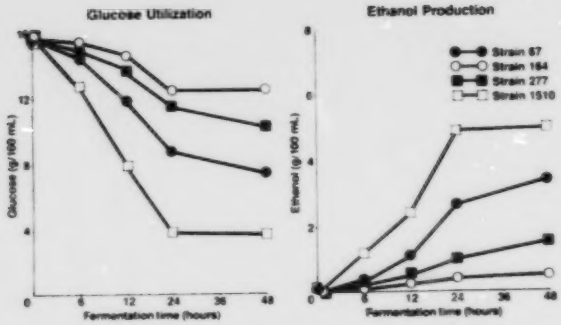

Figure 2. Fermentation of 15% glucose in PYG medium at 40°C by various thermotolerant yeast strains.

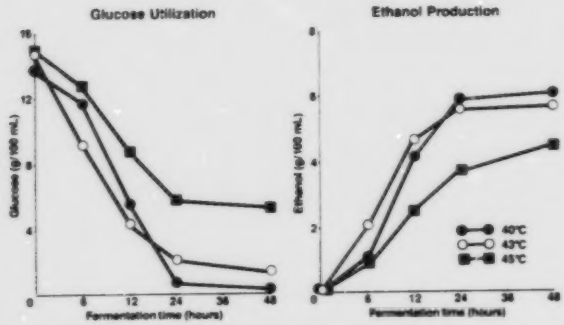

Figure 3. The effect of increasing temperature on 15% glucose fermentation by *Kluyveromyces marxianus* strain 1510 in 2 X PYG medium.

ethanol production was therefore investigated. Figure 4 illustrates the effect of increasing cell inoculum on ethanol production from 15% glucose at 40°C by *Saccharomyces cerevisiae* strain 67. As can be seen, the rate and extent of ethanol production increases with increasing cell inoculum in the range of 0.35% to 4% (w/v). With a 4% (w/v) cell inoculum, complete glucose utilization and maximum ethanol production was observed after 12 h of fermentation. Similar results were observed with other yeast strains examined (data not shown). Thus, increasing the cell inoculum will result in an increase in the rate and extent of glucose utilization and ethanol production and improve fermentation profiles at higher temperatures.

In an attempt to improve the ability of yeast to ferment glucose at higher temperatures, the technique of spheroplast fusion was employed (11,15). The procedure involves the use of two parental strains that are genetically marked with complementary selection markers. The major problem with this method is that many of the yeast strains

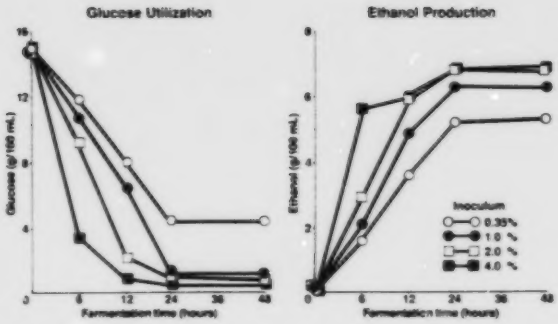

Figure 4. Effect of inoculum size on 15% glucose fermentation by *Saccharomyces cerevisiae* strain 67.

lack selectable markers. Therefore, these strains must first be mutated by such methods as ultraviolet irradiation in order to obtain mutants with selectable markers. These strains are then suitable for fusion experiments. Figures 5 and 6 illustrate the results of the fermentation of 15% glucose at 40°C by two spheroplast fusion products obtained by this technique and their fusion parents. Spheroplast fusion was performed between *Saccharomyces rosei* strain 236 and *Saccharomyces diastaticus* strain 1580. The selectable characteristics of *Saccharomyces rosei* strain 236 are its osmotolerance (i.e., ability to tolerate high sugar concentrations) and its ability to ferment raffinose, whereas *Saccharomyces diastaticus* strain 1580 is able to ferment starch and dextrins and growth at 37°C but is incapable of fermenting raffinose. The fusion products were selected on their ability to ferment raffinose and growth at 37°C. One of the fusion products obtained was observed to have improved fermentation profiles, producing approximately 4.5% (w/v) ethanol from 15% glucose after 24 h at 40°C compared to approximately 2.0% and 0.2% (w/v) ethanol by *Saccharomyces diastaticus* strain 1580 and *Saccharomyces rosei* strain 236, respectively (Figure 5). The combined ability of osmotolerance obtained from *Saccharomyces rosei* strain 236 and temperature tolerance obtained from *Saccharomyces diastaticus* strain 1580 resulted in the fusion products' enhanced ability to ferment glucose at 40°C.

The second spheroplast fusion described was between a mutant of *Saccharomyces cerevisiae* strain 67 which requires adenine for growth and a mutant of *Saccharomyces bayanus* strain 277 which was characterized as respiratory deficient. The fusion products obtained

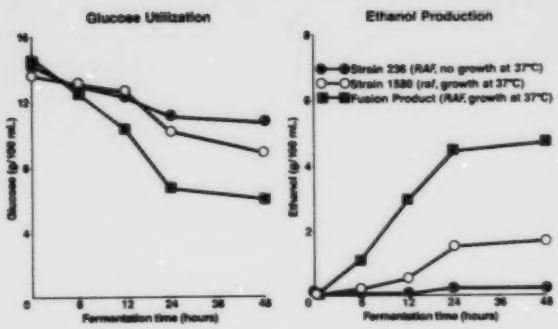

Figure 5. Fermentation of 15% glucose by yeast fusion partners and their fusion product at 40°C.

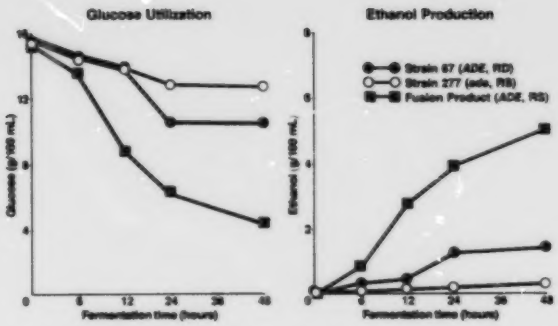

Figure 6. Fermentation of 15% glucose by yeast fusion partners and their fusion product at 40°C.

were therefore selected on their ability to grow on lactate medium containing no adenine. One of the fusion products obtained was observed to have improved fermentation profiles, producing approximately 5% (w/v) ethanol from 15% glucose after 24 h at 40°C compared to approximately 1.4% and 0.3% (w/v) ethanol by *Saccharomyces cerevisiae* strain 67 mutant and *Saccharomyces bayanus* strain 277 mutant, respectively (Figure 6). Thus, as in the previous example, spheroplast fusion can be employed as a technique to improve the ability of yeast to ferment glucose at higher temperatures, as well as improve other characteristics (11). However, it must be emphasized that this technique does not always have a high success rate. Although the examples described demonstrate the usefulness of this technique to improve yeast fermentation ability, there were many cases in which no fusion products could be obtained or there was no improvement in fermentation ability in the fusion products obtained.

In summary, this manuscript reports on the identification and optimization of yeast strains which can effectively ferment glucose at 40°C producing approximately 5% (w/v) ethanol within 24 h. Manipulation of some of these yeast strains by the spheroplast fusion technique was successfully employed to improve the temperature tolerance and ethanol producing ability of these yeast strains.

ACKNOWLEDGEMENTS

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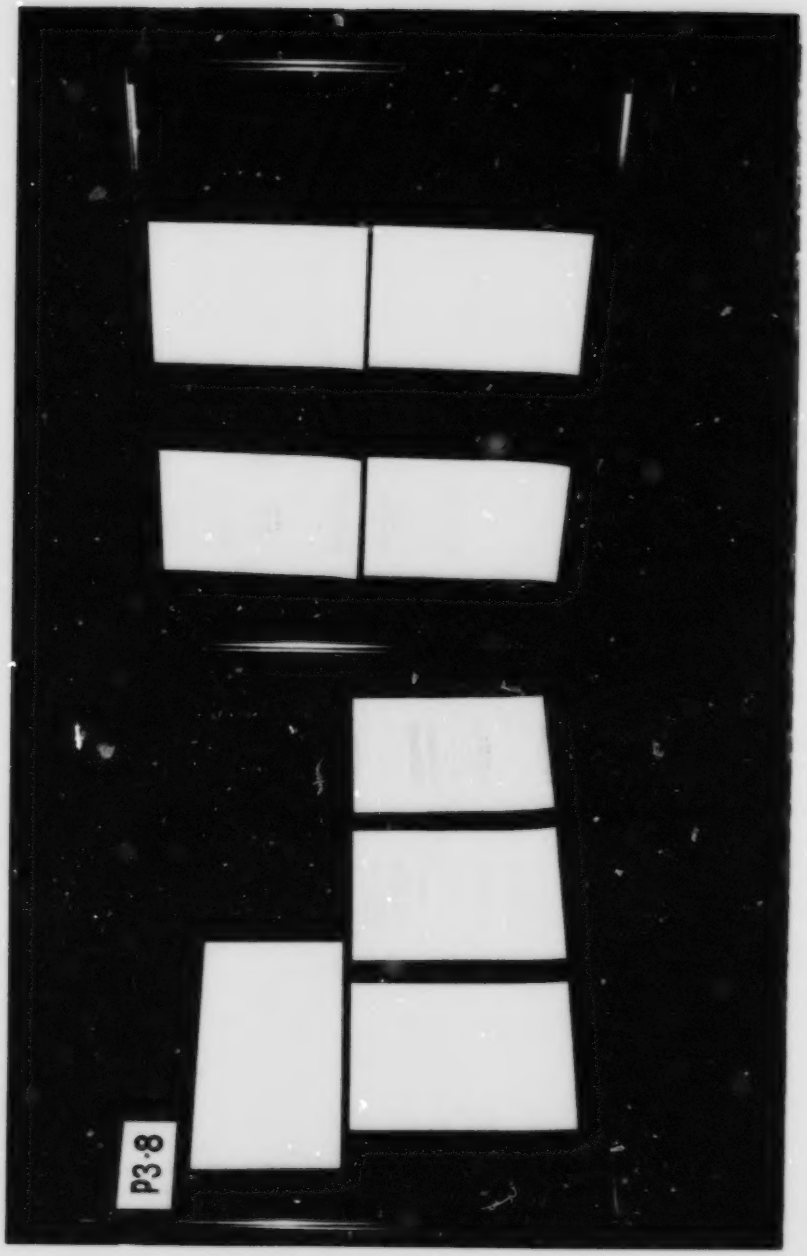
P3·8

Improving the Production of Cellulase Enzymes Used in the Hydrolysis of Lignocellulosic Biomass

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A volumetric cellulase enzyme productivity of 600 mg/L/h was achieved in a fed batch culture of T. reesei. Extracelluar protein concentrations in excess of 70 g/L were attained. These results are unprecedented for a batch or fed batch culture of a cellulolytic microorganism. T. reesei was successfully propagated with enzyme production in both 20 and 1200 L continuous stirred tank reactor (CSTR) systems. A volumetric cellulase enzyme productivity of 730 mg/L/h was achieved in a 20 L CSTR culture of T. reesei. This result is unprecedented for a culture of a cellulolytic microorganism. Scale-up of the CSTR fermentation system to 1200 L is in progress at Iogen's Ottawa biomass processing facility. At a dry cell density of 23 g/L the scaled-up CSTR fermentation of T. reesei exhibited oxygen transfer properties which were dependent upon power input and aeration. The dependence of oxygen transfer upon both power input and aeration was consistent with literature reports for non-Newtonian fermentation broths. The results from the scaled-up CSTR indicate that the oxygen transfer characteristics of the system will support a volumetric cellulase productivity of at least 800 mg/L/h and possibly as high as 1200 mg/L/h.

INTRODUCTION

The cellulase enzyme used to catalyze the hydrolysis of lignocellulose into sugar is produced by a strain of the wood rotting fungus T. reesei. During cellulase production, a pure suspension of the producer organism is inoculated into a stirred tank, called a fermentor, contain -ing a sterile medium. The inoculated medium is stirred and aerated. The pH and temperature are controlled at levels optimal for growth of the organism and production of cellulase.

Cellulase production can be performed in a batch system, a fed batch system or a continuous system. In a batch system the production of cellulase ceases when the substrate is depleted. However, due to catabolite repression, the production of cellulase is only induced in the organism during the late stages of a batch, i.e. when substrate concentrations are low and nearly depleted. In a fed batch system a sterile solution of substrate is slowly introduced into the fermentor at such a rate as to maintain a low substrate concentration. This serves to prolong the period of cellulase production. In a continuous system a sterile solution of substrate is slowly introduced into the fermentor and a portion of the broth is removed at an equal rate so as to keep the broth volume constant. In this system, the period of cellulase production may be maintained as long as desired. The fermentation broth attains a steady state at which all conditions in the fermentor remain constant and favourable for cellulase production.

The key quantitative factor that describes the performance of a cellulase production system is the rate per unit volume at which a fermentor produces cellulase, i.e. the volumetric cellulase productivity (mg/L/h). Increasing the volumetric productivity saves significant amounts of capital and operating costs by reducing the number of fermentors needed to make a given amount of enzyme.

We have previously reported the highest known volumetric cellulase productivity, 380 mg/L/h (Foody, 1984). This report reviews our progress in further increasing productivity.

FIGURE 1

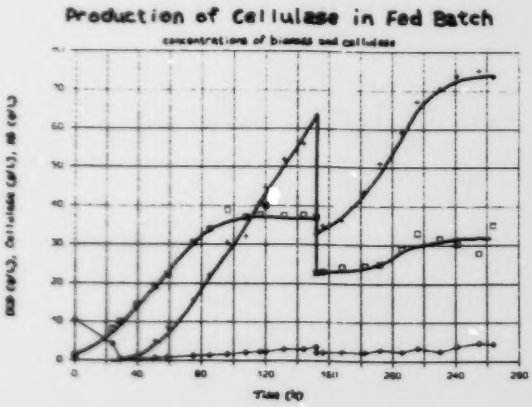

Figure 1. The production of cellulase by T. reesei in a 20 L fed batch stirred tank reactor with continuous harvest after 30 h. The broth was diluted with a mineral nutrient solution at the 150 h mark. The dry cell density (DCD) is represented by open squares; cellulase enzyme is represented by crosses; residual substrate (RS) is represented by open diamonds.

FED BATCH FERMENTATION

In a 20 L fed batch stirred tank reactor a cellulase concentration of 60 g/L and a volumetric cellulase productivity of 600 mg/g/h was achieved after 150 h of culture with a 290 g/L carbohydrate feed stream (Figure 1). A fed batch culture of this duration requires the supplementary addition of mineral nutrients. Following such an addition the volumetric productivity was stable at 600 mg/L/h for a further 100 h.

Extracellular cellulase enzyme concentrations exceeded 70 g/L after 240 h of culture, which is exceedingly high. To our knowledge no other enzyme production system achieves such a high concentration of extracelluar protein. However, at fermentation broth concentrations in excess of 60 g/L the cellulase enzyme was unstable. The specific activity of the cellulase produced dropped significantly below 1.0 IU/mg.

FIGURE 2

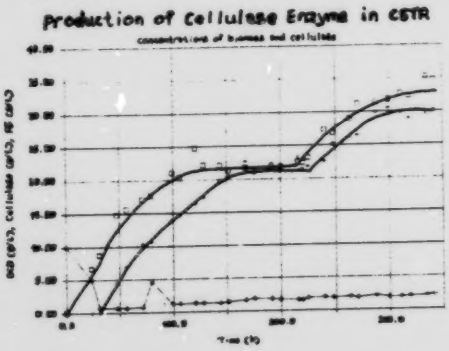

Figure 2. The propagation of T. reesei with cellulase production in a 20 L CSTR. The dilution rate of the system was 0.018 h-1. The dry cell density (DCD) is represented by open squares; cellulase enzyme is represented by crosses; residual substrate (RS) is represented by open diamonds.

CONTINUOUS FERMENTATION

In a 20 L CSTR a steady state of 22 g/L dry cell density and 22 g/L cellulase was achieved with a 85 g/L carbohydrate feed stream (Figure 2). The steady state volumetric productivity was 400 mg/L/h.

A steady state of 33 g/L dry cell density and 30 g/L cellulase was achieved with a 126 g/L carbohydrate feed stream (Figure 2). The steady state volumetric productivity was 570 mg/L/h.

In a 20 L CSTR culture of T. reesei with a 180 g/L carbohydrate feed stream a steady state dry cell density of 41 g/L was attained. The volumetric productivity of this system was 730 mg/L/h. The magnitude of this productivity is unprecedented, being almost twice as high as the previous highest reported (Foody, 1984).

FIGURE 3

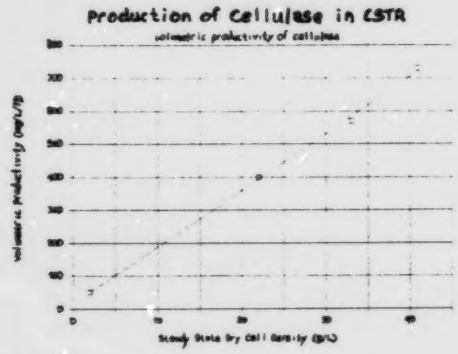

Figure 3. Steady state dry cell densities and corresponding volumetric cellulase productivities attained in 20 L CSTR cultures of T. reesei at Iogen. In each case the dilution rate of the culture was 0.02 h-1.

In CSTR cultures volumetric cellulase productivities are directly proportional to the steady state dry cell densities. This relationship is characterised by the specific cellulase productivity, qp, of T. reesei (equation 1). The qp of T. reesei is given by the slope of the data in Figure 3; i.e. 18 mg/g/h.

$$P = qpX \qquad (1)$$

where: P represents the volumetric cellulase productivity (mg/L/h)

qp represents the specific cellulase productivity of T. reesei (mg/g/h)

X represents the steady state dry cell density of T. reesei in CSTR culture (g/L)

Unfortunately the bulk characteristics of T. reesei fermentation broth preclude operation in small scale vessels at dry cell densities in excess of 40 g/L. These material handling problems (foaming, bulk density changes etc.) are mitigated in pilot scale equipment.

THE ROLE OF OXYGEN TRANSFER

The volumetric cellulase productivity of the CSTR system is inherently limited by its oxygen transfer capacity.

Equation 1 indicates that in order to increase the volumetric productivity of cellulase from T. reesei in CSTR culture the steady state dry cell density must be increased. At a constant dilution rate this will require an increase in the concentration of the feed stream and thus an increase in the system's carbon uptake rate, CUR (mmol carbon/L/h). For T. reesei the yield of products from substrate, YP/S (mmol carbon in products/mmol carbon assimilated), is 0.50; thus, the CO_2 evolution rate, CER (mmol CO_2/L/h) is one half of CUR. If the respiration quotient, RQ (CER/oxygen uptake) is 1.0, which is true for our aerobic culture assimilating a carbohydrate, then the oxygen uptake rate, OUR (mmol oxygen/L/h) will be exactly equal to the CER and will increase proportionally with the dry cell density.

However, the oxygen transfer coefficient, kLa, must increase proportionally with OUR if the concentration of dissolved oxygen in the broth is to remain constant (equation 2).

$$kLa = OUR/(C^* - CL) \qquad (2)$$

where: kLa represents the oxygen transfer coefficient (mmol O_2/L/h/atm O_2)

OUR represents the oxygen uptake rate (mmol O_2/L/h)

C* represents the oxygen concentration of the inlet air (atmospheres of O_2)

CL represents the oxygen concentration in the broth (equivalent atmospheres of O_2)

FIGURE 4

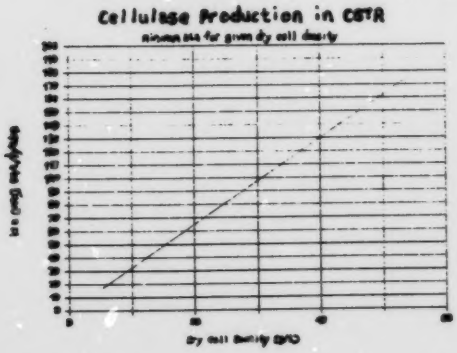

Figure 4. This figure shows the minimum value of the oxygen transfer coefficient kLa which must be maintained to support a given steady state dry cell density in a CSTR reactor. The limitation is calculated by assuming a minimum allowable dissolved oxygen of 20% with a reactor back pressure of 20 psig, a dilution rate of 0.018 h-1, a yield of products from substrate, YP/S, of 50% and a specific cellulase productivity of 18 mg/g/h.

Thus, kLa must also increase to accommodate increases in the steady state dry cell density (Figure 4).

Clearly then, the productivity of the CSTR system is limited by kLa. The kLa required to maintain a minimum concentration of dissolved oxygen increases proportionally with the productivity (Figure 5). To achieve a volumetric cellulase productivity of 800 mg/g/h, the goal for this project, a minimum kLa of 150 mmol/L/h/atm O_2 is required.

FIGURE 5

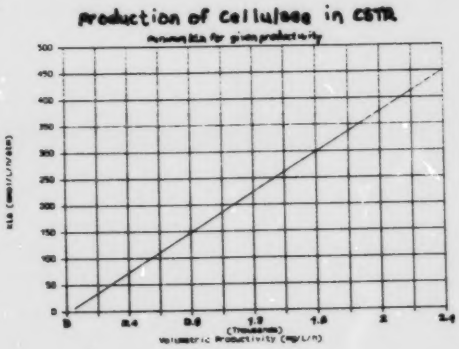

Figure 5. This figure shows the minimum value of the oxygen transfer coefficient kLa which must be maintained to support a given productivity in a CSTR reactor. The limitation is derived from the data in Figure 3 and the relationship in Figure 4.

MEASUREMENTS OF OXYGEN TRANSFER

The oxygen transfer in a stirred tank fermentor is known to be related to both agitation and aeration in the following form (Cooper et al., 1944):

$$kLa = C(Pg/VL)^a(vs)^b \qquad (3)$$

where: C represents a constant

Pg/VL represents the gassed power input per unit volume (hp/100 gal)

a represents a constant

vs represents the superficial air velocity, i.e. the volumetric aeration rate divided by the cross sectional area of the broth (cm/min)

b represents a constant

FIGURE 6

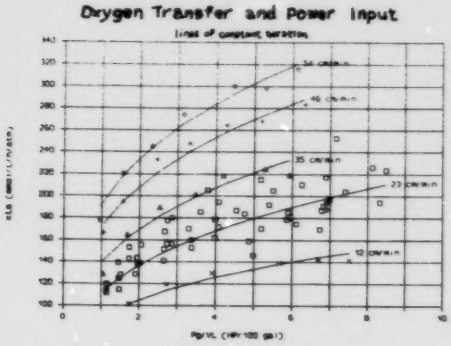

Figure 6. The dependence of the mass transfer coefficient kLa on gassed power (Pg/VL) in a 1200 L CSTR culture of T. reesei. The open triangles represent data collected at various gassed powers with superficial air velocity (vs) held constant. The lines represent a power law model with exponent 0.30 fit to the data from each series of constant superficial air velocity tests.

Data collected from Iogen's 1200 L CSTR during scale-up of the cellulase production process (now in progress) indicated that at a constant superficial air velocity kLa increases with the 0.30 power of Pg/VL (Figure 6). These findings are in close correspondence with Taguchi et al. (1968) who found that kLa varied with the 0.33 power of Pg/VL for a non-Newtonian fermentation broth.

Further, the data indicated that at a constant gassed power kLa increases with the 0.50 power of vs (Figure 7). These findings are again in close correspondence Taguchi et al. (1968) who found that kLa varied with the 0.56 power of vs for a non-Newtonian fermentation broth.

FIGURE 7

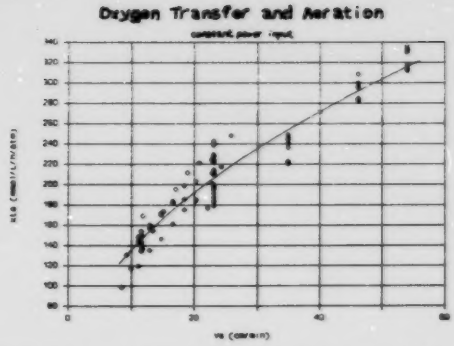

Figure 7. The dependence of the mass transfer coefficient kLa on superficial air velocity (vs) in a 1200 L CSTR culture of T. reesei. The open diamonds represent data collected at various superficial air velocities with gassed power (Pg/VL) held constant. The line represents a power law model with exponent 0.50 fit to the data.

A kLa as high as 320 mmol/L/h/atm O2 was achieved in Iogen's 1200 L CSTR which is significantly in excess of the kLa required to maintain a volumetric cellulase productivity of 800 mg/L/h, i.e. 150 mmol/L/h/atm O2.

Therefore Figure 5 suggests that large scale volumetric cellulase productivities in excess of 1200 mg/L/h (i.e. a kLa of 220 mmol/L/h/atm O2), substantially higher than any previously reported, may be attained.

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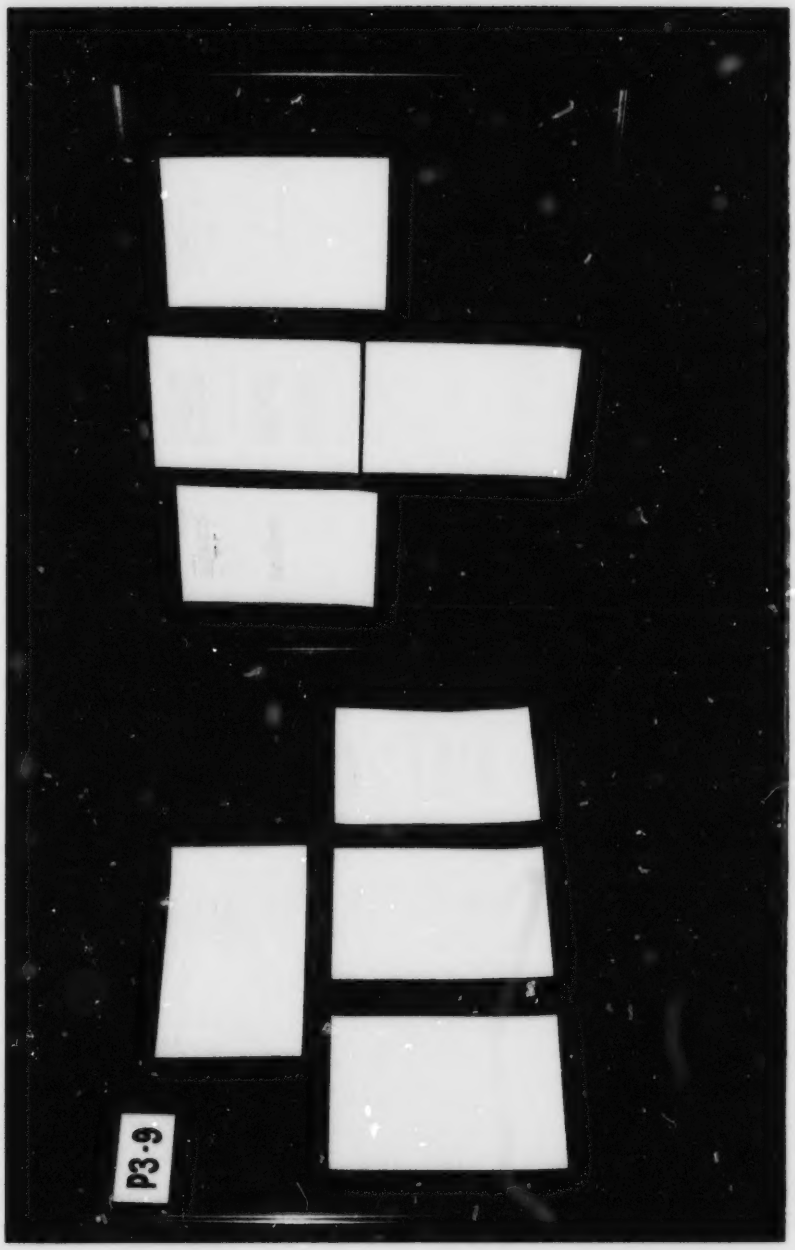
P3-9

OPTIMIZATION OF A PENTOSE FERMENTATION SYSTEM FOR EXPLODED WOOD SUGARS

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Organic nitrogen media supplements have a profound effect on the rate, yield and product profile of the alcoholic fermentation of xylose by P. stipitis R. The rate and yield of ethanol fermentation may be selectively enhanced by the addition of corn steep liquor (CSL) to the fermentation. In dilute batch culture of pure xylose the maximum specific ethanol production rate in the presence of CSL was 0.103 g/g/h while the maximum apparent ethanol yield in the presence of CSL was 0.50 g/g. On the other hand, the addition of yeast and malt extracts plus peptone (YMP) alone to the fermentation results in the formation of a significant quantity of the by-product xylitol.

Ethanol inhibition of the alcoholic fermentation of xylose by P. stipitis R is also strongly influenced by media supplements. With CSL as a media supplement the specific xylose uptake rate was reduced by half in the presence of 40 g/L ethanol; with YMP a similar reduction was observed in the presence of 20 g/L ethanol. The respiration quotient of a culture of P. stipitis R on xylose is a fundamental parameter governing ethanol yield. In a continuous stirred tank reactor (CSTR) culture of P. stipitis R with a mixed glucose and xylose substrate, supplemented by YMP, ethanol yield increased as the respiration quotient increased. Theoretical considerations of the effect of respiration quotient on ethanol yield, supported by our CSTR results, suggest that ethanol yields in excess of 0.40 g/g can only be achieved in CSTR under near anaerobic conditions.

INTRODUCTION

In an ethanol from biomass process glucose and xylose are produced from the polysaccharide component of the lignocellulose. Current commercially available alcoholic fermentation processes will only convert the glucose fraction to ethanol. Development of an efficient xylose fermentation system could increase ethanol yields from lignocellulose by as much as 40%.

In a microbial alcoholic fermentation process the key kinetic parameters which describe the system are:

1) the specific substrate uptake rate, qs (g substrate/g dry cells/h)

2) the specific ethanol production rate, qp (g ethanol/g dry cells/h)

3) the ethanol yield from the substrate, YE/S (g ethanol/g substrate)

4) the concentration of inhibitor, such as the end product ethanol, which reduces qs by half, Ki (g/L)

A variety of yeasts have been touted as xylose fermenting organisms. These includes species of the genera Pichia, Candida and Brettanomyces as well as Pachysolen tannophilus (Maleszka and Schneider, 1982; Gong et al., 1983; Toivola et al., 1984; Prior et al., 1989). A specially adapted strain of P. stipitis, designated "R", has recently shown promise (Parekh et al., 1986). However, the efficiency of the best known xylose fermenting organisms -- in terms of qp and YE/S or both -- is still substantially less than that of Saccharomyces cerevisiae fermenting glucose (Jeffries, 1985).

FIGURE 1

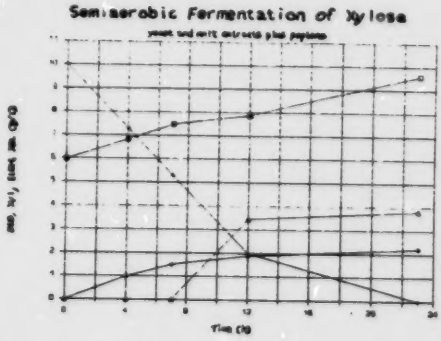

Figure 1. The semiaerobic alcoholic fermentation of pure xylose in with the addition of YMP. Open squares represent the dry cell density (DCD), crosses represent xylose concentration (Xyl), open diamonds represent ethanol concentration (EtOH), open triangles represent xylitol concentration (XOL).

MEDIA EFFECTS IN BATCH CULTURE

In a dilute, lightly aerated "semiaerobic" batch culture of P. stipitis R on pure xylose with the addition of YMP, a source of organic nitrogen, a mixture of products was observed (Figure 1). Ethanol was produced at a maximum qp of 0.038 g/g/h and in a yield of 0.22 g/g. Xylitol, the initial catabolic product of xylose assimilation, was produced in a yield of 0.38 g/g.

With the addition of CSL, an alternate source of organic nitrogen, only ethanol production was observed (Figure 2). The rate of the fermentation was substantially enhanced relative to xylose plus YMP. A maximum qp of 0.075 g/g/h was observed. Ethanol yield was also increased to an apparent 0.50 g/g.

In the presence of both YMP and CSL the highest qp was observed, 0.103 g/g/h (Figure 3). An apparent ethanol yield of 0.50 g/g was achieved.

FIGURE 2

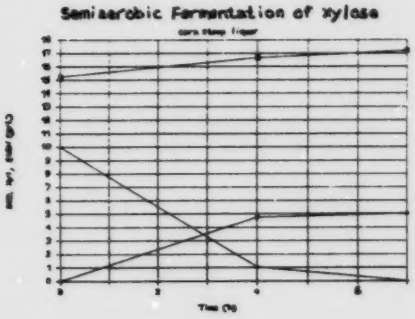

Figure 2. The semiaerobic alcoholic fermentation of pure xylose with the addition of CSL. Open squares represent the dry cell density (DCD), crosses represent xylose concentration (Xyl), open diamonds represent ethanol concentration (EtOH).

FIGURE 3

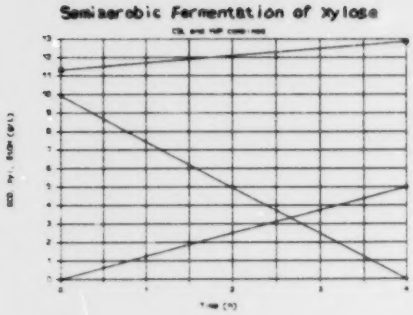

Figure 3. The semiaerobic alcoholic fermentation of pure xylose with the addition of both YMP and CSL. Open squares represent the dry cell density (DCD), crosses represent xylose concentration (Xyl), open diamonds represent ethanol concentration (EtOH).

LIMITATIONS TO BATCH CULTURE

While our results -- in terms of yield of ethanol -- are quite good two points should be noted:

1) these are extremely dilute cultures of xylose

2) a substantial amount of xylose is required to produce the large inoculum

In order to ferment more concentrated solutions of xylose the effects of product inhibition must be evaluated. Exogenous ethanol added to dilute "semiaerobic" batch cultures inhibited the rate of xylose uptake (Figure 4). The extent of inhibition was dependent upon the media supplement. Thus, in the presence of YMP, Ki was 20 g/L ethanol while, in the presence of CSL, Ki was 40 g/L ethanol.

One method of recouping the investment of substrate in cell growth is to recycle the yeast after fermentation. However our preliminary results suggest that YE/S is not stable in successive batch cultures. Ethanol yields drop by 30% over three successive batches with yeast recycle.

A second alternative is to operate a continuous stirred tank reactor (CSTR) fermentation. In a CSTR culture growth of fresh yeast is constant and steady states of ethanol production may be achieved. Continuous yeast growth represents a slight decrease in substrate

available for ethanol production and, therefore, a decrease overall ethanol yield; nevertheless, ethanol yields in excess of 0.40 g/g are attainable. CSTR alcoholic fermentation is discussed below.

FIGURE 4

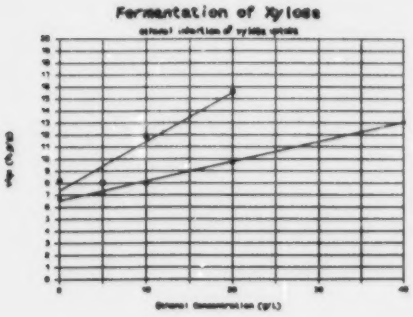

Figure 4. The inhibition of xylose uptake by ethanol. Each data point represents the fermentation of a dilute solution of xylose under semiaerobic conditions in the presence of exogenous ethanol. Open squares represent fermentations supplemented with YMP, open triangles represent fermentations supplemented with CSL.

RESPIRATION QUOTIENT EFFECTS

Ultimately a biological system will catabolize a substrate in order to produce energy for the maintenance of cellular structures and growth. Thus, in an alcoholic fermentation a rational basis for understanding the yields of ethanol, cell mass and CO_2 from the substrate may be developed by considering the yields of energy from ethanol production and complete oxidation of the substrate as well as the cellular energy requirements for growth and maintenance. The extent of ethanol production versus complete oxidation of the substrate will be governed by the aerobic state of the system.

The respiration quotient — RQ, the ratio of CO_2 evolution to O_2 consumption — is the fundamental parameter describing the aerobic state of a biological system. Conventionally, terms such as aerobic, semiaerobic and anaerobic are used loosely without regard to RQ.

In a respiring aerobic system in which xylose is completely oxidized, CO_2 evolution exactly balances O_2 consumption and RQ is unity (equation 1).

$$C_5H_{10}O_5 + 5O_2 \quad 5CO_2 + 5H_2O + 31.67ATP \quad (1)$$

On the other hand if ethanol is being produced then, on a molar basis, CO_2 evolution equals ethanol production, oxygen consumption is zero and RQ is infinite (equation 2).

$$C_5H_{10}O_5 \quad 1.67C_2H_6O + 1.67CO_2 + 1.67ATP \quad (2)$$

The maximum yield of ethanol by this reaction is 0.51 g/g.

An alternative mechanism, considered by some to represent the conversion of xylose to ethanol by yeasts (Bruinenberg et al, 1983), requires the diversion of a portion of the carbon flow to the hexose monophosphate (HMP) cycle. This is because the first reaction of xylose catabolism, the reduction of xylose to xylitol with the concomitant oxidation of the coenzyme NADPH to NADP, requires a steady supply of NADPH which, it is thought, can only be generated by the oxidative reactions of the HMP cycle. By this mechanism the production of ethanol from xylose should proceed as in equation (3).

$$C_5H_{10}O_5 + 0.5O_2 \quad 1.5C_2H_6O + 2CO_2 + 0.5H_2O + 4.5ATP \quad (3)$$

The maximum yield of ethanol in this case is 0.46 g/g. This is because CO_2 is evolved during the conversion of pyruvate to acetaldehyde by pyruvate decarboxylase, as in conventional glucose fermentation, and additionally in the HMP cycle during the conversion of 6-phosphogluconate to ribulose-5-phosphate by 6-phosphogluconate dehydrogenase.

This mechanism also requires the consumption of a small amount of oxygen. The oxygen is required to recycle the coenzyme NAD from its reduced form, NADH, via electron transport phosphorylation. NAD is required for the second reaction of xylose catabolism, i.e. the reduction of xylitol to xylulose. The requirement for oxygen indicates that, if the mechanism is true, xylose fermentation should not be possible at an RQ greater than 4.0.

A third fate of the substrate is assimilation into cellular structures, i.e. growth. If we use $C_{29}H_{48}O_{14}N_4$ as a molecular formula for a yeast cell (Cooney, 1987) and assume only a complete carbon balance, then equation 4 represents the growth of the yeast.

$$C_5H_{10}O_5 + (127/YATP)ATP \quad 0.17C_{29}H_{48}O_{14}N_4 \quad (4)$$

where: YATP represents the yield of cells from ATP, our experimental results estimate YATP to be 3.0 g cells/mol ATP

In order to investigate the effect of RQ on product distribution equations 1, 3 and 4 are

generalized to equations 5, 6 and 7.

a1C5H1005 + 5a1O2 5a1CO2 + 5a1H2O + 31.67a1ATP (5)

a2C5H1005 + 0.5a2O2 1.5a2C2H6O + 2a2CO2 + 0.5a2H2O + 4.5a2ATP (6)

a3C5H1005 + 42.33a3ATP 0.17a3C29H48O14N4 (7)

where: a1 represents the mole fraction of substrate which is completely oxidized

a2 represents the mole fraction of substrate which is fermented to ethanol

a3 represents the mole fraction of substrate which is assimilated in cellular structures

A system of three equations and three unknowns, augmented matrix A, may then be derived for this system.

$$(A)\quad \begin{matrix} 1 & 1 & 1 & a1 & 1 \\ 5(1-RQ) & 0.5(4-RQ) & 0 & a2 & = 0 \\ 31.67 & 4.5 & -42.33 & a3 & 0 \end{matrix}$$

Matrix A can be solved for 1.0<RQ<4.0 yielding theoretical predictions for the yield of ethanol, cell mass and CO2.

In a CSTR culture of P. stipitis R with a feed stream consisting of a mixture of glucose and xylose supplemented with YMP, steady states at various RQ's were achieved. The yields of cell mass and ethanol were in reasonable agreement with theoretical predictions (Figure 5).

FIGURE 5

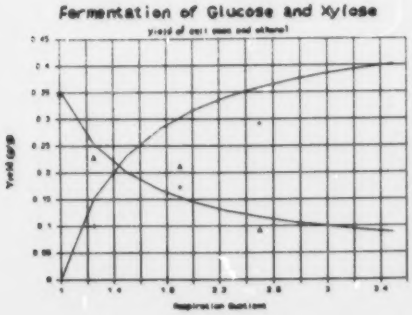

Figure 5. The Fermentation of a mixture of glucose and xylose in CSTR culture supplemented with YMP. The yields of cell mass, open triangles, and ethanol, crosses, are shown as a function of RQ. Each data point represents a steady state achieved in CSTR. The lines represent the theoretical yields of the two products as RQ varies.

FIGURE 6

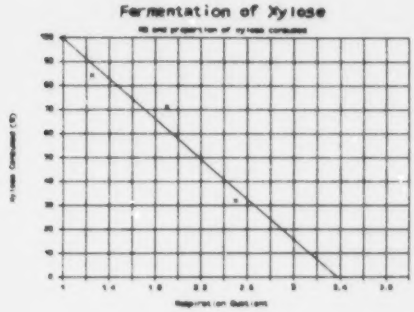

Figure 6. The fermentation of a mixture of glucose and xylose in CSTR culture supplemented with YMP. The xylose uptake, represented as a percent of the xylose fed, is shown as function of RQ. Each point represents a steady state achieved in CSTR.

In CSTR culture, as RQ increased the uptake of xylose decreased (Figure 6). By extrapolation, it would appear that xylose uptake would cease altogether at an RQ of roughly 3.4, which is reasonably close to the RQ of 4.0 which theory suggests is the maximum allowable for xylose fermentation.

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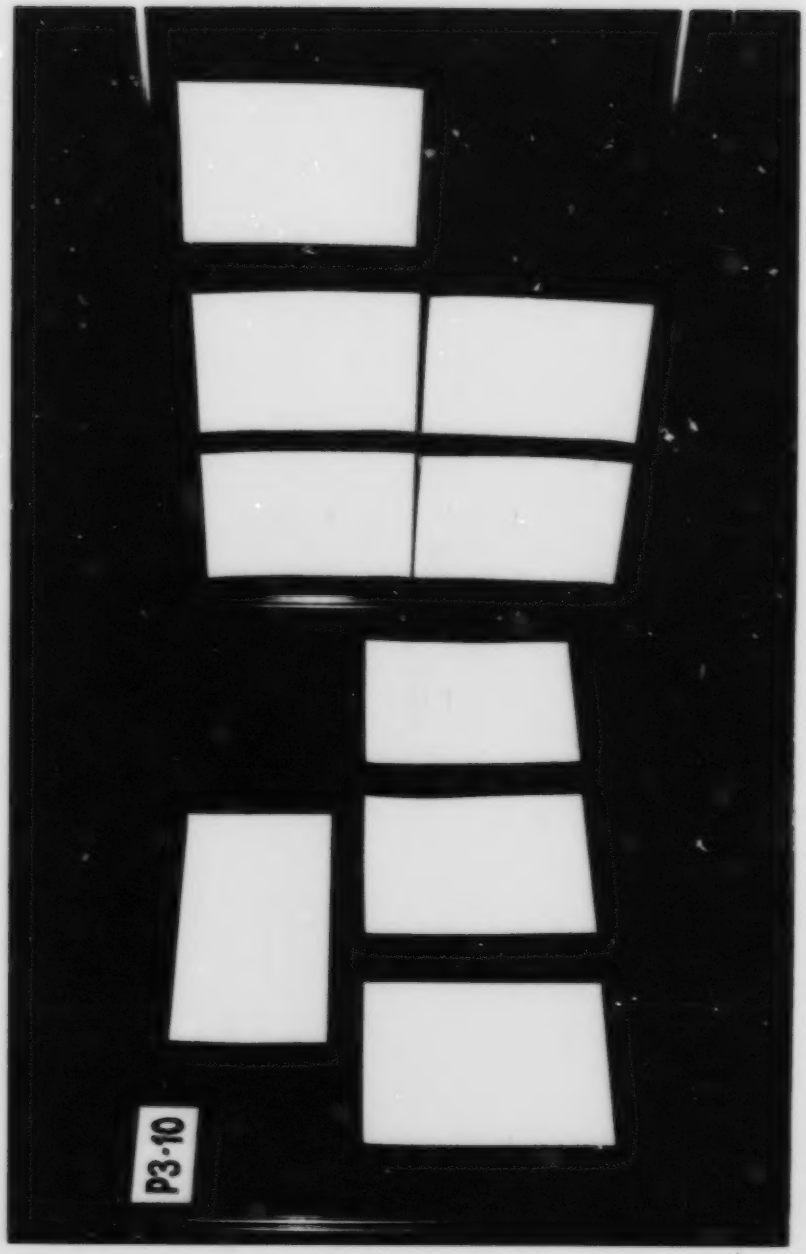
P3-10

KINETIC STUDY OF EXPLODED WOOD HYDROLYSIS

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The enzymatic hydrolysis of cellulose by cellulase has been the subject of intensive study for many years. Nonetheless, there is no consensus on the quantitative role of the various aspects of the cellulose conversion process. The key elements in the kinetics of hydrolysis include: adsorption of the cellulase onto its substrate, initial rapid hydrolysis of the substrate by cellulase, and a slowdown in hydrolysis rate due to a combination of increasing substrate recalcitrance, time dependent enzyme inactivation and product inhibition.

We will describe a mechanistic model of Exploded Wood cellulose hydrolysis that is based entirely on independently verified experimental data. In addition to providing a means to study the kinetic mechanism of hydrolysis, the model will address the various hydrolysis issued on Exploded Wood cellulose, a substrate which has not previously been studied quantitatively.

Numerous models of the enzymatic hydrolysis of several cellulosic materials have been published and are extensively reviewed by Gilbert and Tsao (1985)1. In its most useful form, a mode can help elucidate the mechanisms of a process by providing a quantitative means to assess assumed modes of behaviour. To do so, however, all of a model's assumptions must be verified independently. On the other hand, many kinetic models start with assumed reaction mechanisms and then use non linear regression routines to fit several kinetic constants to the available data. These models are useful for interpolating between known results, but do not help assess the reaction mechanism and may not extrapolate accurately beyond the measured range of data. Unfortunately, many of the models presented in the literature include one or more unverified assumptions.

The basic elements of cellulose hydrolysis and the main areas of dispute that are characterized in models are summarized below.

Enzyme Adsorption

Cellulase adsorbs onto and binds to its insoluble substrate, cellulose. The equilibrium concentration of enzyme bound to substrate and enzyme in solution is widely reported to be described by a Langmuir isotherm. The time reported for the system to reach adsorption equilibrium ranges from essentially zero to several days. The accessible surface area, which is measured in terms of the maximum amount of enzyme adsorbed, is generally in the range of 20-50 mg protein/g cellulose.

Initial Rate of Hydrolysis

Several studies include a term for initial rate of hydrolysis. Generally the initial rate of hydrolysis is described as directly proportional to the concentration of adsorbed enzyme. This formulation is consistent with classical Michaelis-Menten kinetics. However, published "initial rate" hydrolyses often last 12-30 hours, during which time substantial changes in concentrations and rates may have occurred.

Enzyme Inactivation

Cellulase enzyme has been widely reported to be stable in solution. Only one of the published models includes a term for a time-dependent enzyme activity loss. This report was based on the hydrolysis of Solka floc but did not include any experimental verification of the degree of cellulase enzyme inactivation.

Substrate Susceptibility

Virtually all of the models summarized by Gilbert and Tsao assume that the rate of hydrolysis decreases because the substrate becomes recalcitrant to hydrolysis. Some of the mechanisms cited are the loss of accessible surface area; the existence of easily-hydrolyzed (amorphous) and difficult (crystalline) fractions; and, the existence of glucose oligomers of a certain degree of polymerization that are resistant to hydrolysis.

Product Inhibition

Cellobiose and glucose inhibit the action of the cellulase enzyme, and this is incorporated into almost all of the published models. Several types of inhibition have been reported and used in hydrolysis models, including competitive, uncompetitive, and noncompetitive inhibition. These models have used inhibition constants differing by as much as 2 order of magnitude. In many cases, regardless of which mechanism is assumed, the experiments used to determine inhibition constants do not take into account experimental difficulties, such as the accumulation of cellobiose when high levels of glucose are present.

Beta-glucosidase

The conversion of cellobiose to glucose is catalyzed by the enzyme beta-glucosidase. Beta-glucosidase is widely reported to follow Michaelis-Menten kinetic in this reaction, with glucose acting as an inhibitor. The literature contains many descriptions of inhibition models for glucose, including competitive and noncompetitive inhibition.

A mechanistic model of cellulose hydrolysis has been developed. Kinetic constants for each of the processes listed above have been determined for Exploded Wood cellulose, a lignocellulosic crystalline material, and two purified celluloses, Sigmacell (crystalline) and Acid-Swollen cellulose (amorphous). These kinetic constants have been combined, without arbitrary manipulation, in a computer model. Predicted results have been compared with a wide range of experimental data.

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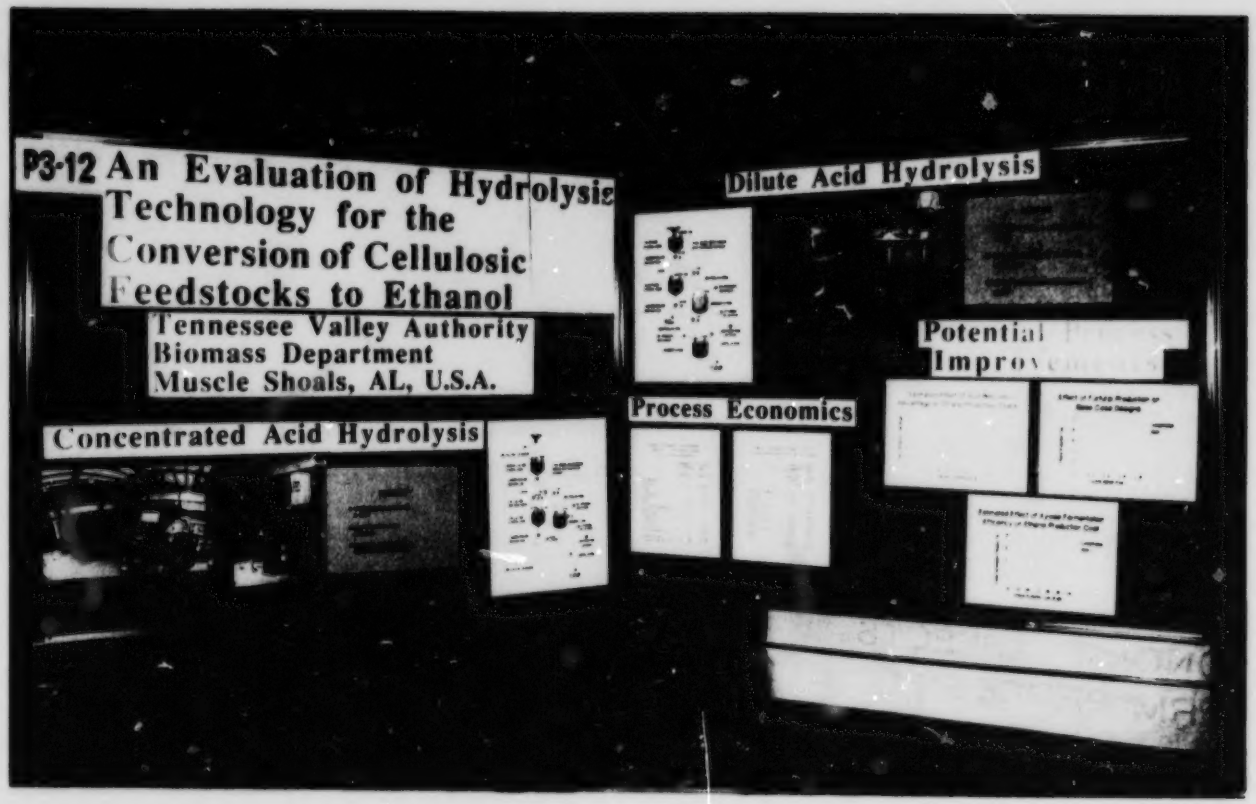
P3-12 An Evaluation of Hydrolysis Technology for the Conversion of Cellulosic Feedstocks to Ethanol
Tennessee Valley Authority
Biomass Department
Muscle Shoals, AL, U.S.A.
Concentrated Acid Hydrolysis
Dilute Acid Hydrolysis
Process Economics
Potential

AN EVALUATION OF HYDROLYSIS TECHNOLOGY FOR THE CONVERSION OF CELLULOSIC FEEDSTOCKS TO ETHANOL AND OTHER CHEMICALS

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Tennessee Valley Authority
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The Tennessee Valley Authority (TVA) is involved in the development of acid hydrolysis processes for the conversion of cellulosic feedstocks to ethanol and other chemicals. Two processes are currently being developed, a dilute sulfuric acid hydrolysis process and a concentrated sulfuric acid hydrolysis process, for converting cellulosic feedstocks to sugars for ethanol production. Both processes are being developed in laboratory-, bench-, and pilot-scale studies. Ethanol yields from the two processes are 63 gal/t using dilute acid hydrolysis and 72 gal/t using the concentrated acid hydrolysis.

An economic assessment of the two processes has been conducted using a base-case commercial-scale design for producing 11 M gal/yr of ethanol. Hardwoods and corn stover are used as feedstocks for the dilute and concentrated sulfuric acid hydrolysis processes, respectively. This paper will evaluate the effects of both internal and external factors on ethanol production costs. The sensitivity of these costs to technology, market, and economic changes will be presented.

La Tenessee Valley Authority (TVA) participe á la mise au point de procédés d'hydrolyse acide applicables á la transformation de matiéres cellulosiques en éthanol et en autres produits chimiques. Deux procédés sont actuellement en cours de développement, á savoir un procédé d'hydrolyse á l'acide sulfurique dilué et un procédé d'hydrolyse á l'acide sulfurique concentré. Ces procédés visent á transformer des matiéres cellulosiques en sucres en vue de la production d'éthanol. La mise au point se fait á l'échelle du laboratoire et á l'échelle pilote. Le rendement d'éthanol est de 63 gal/t dans le cas de l'hydrolyse á l'acide dilué et de 72 gal/t dans de case de l'hydrolyse á l'acide concentré.

On a effectué une évaluation économique des deux méthodes basée sur la production de 11 M gal d'éthanol/an, d'aprés une étude de cas commerciale. Du bois de feuillus et du fourrage de maïs servent respectivement de matiére de base, pour les procédés d'hydrolyse á l'acide sulfurique dilué et á l'acide sulfuriqué concentré. Dans cette communication, on évaluera les effets de facteurs internes et externes sur le coût de la production de l'éthanol. On décrira la sensibilité des coûts á l'égard des changements touchant la technologie, le marché et l'économie sera présentée.

INTRODUCTION

The Tennessee Valley Authority (TVA) is a Federal agency created in 1933 by a United States Congressional act for regional economic development by more efficient resource utilization. TVA's biomass program, formed in 1980, focuses on applied research and development of technology for producing fuels and chemicals from renewable resources.

Two acid hydrolysis processes for conversion of cellulosic feedstocks to ethanol and other chemicals are being developed at TVA. A two-stage, low-temperature (212°F), low-pressure (1 atm) concentrated sulfuric acid hydrolysis process has been developed and evaluated in laboratory-, bench-, and pilot-scale (4-ton-of-feedstock-per-day) studies using corn stover as feedstock. Cellulose and hemicellulose conversion efficiencies have averaged over 90%, resulting in ethanol yields of over 70 gallons per ton of dry feedstock (Barrier et al., 1985). The second process, a two-stage dilute sulfuric acid hydrolysis process, is used to convert hardwoods into fermentable sugars at high temperatures (266°F) and pressures (10 atm). Laboratory-, bench-, and pilot-scale (2-ton-of-feedstock-per-day) evaluations of the process have resulted in sugar yields equivalent to 60 gallons of ethanol per ton of dry

wood (Baker, et al., 1986). Flow diagrams of the concentrated and dilute acid hydrolysis processes are given in Figures 1 and 2.

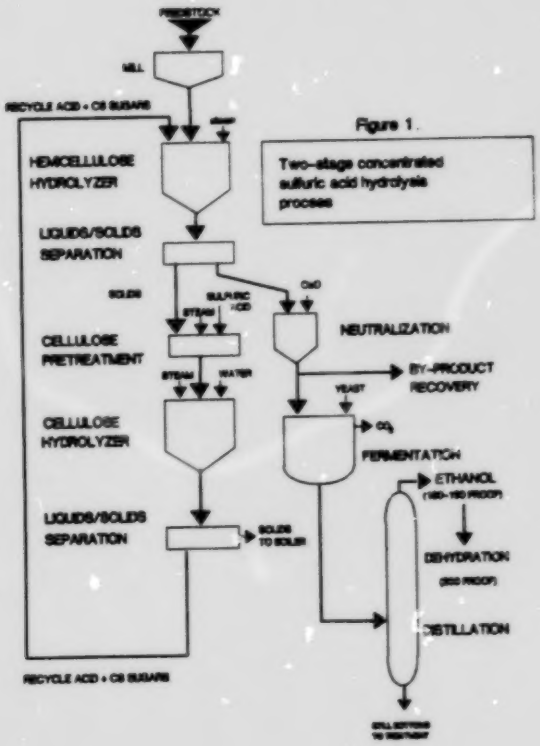

Figure 1.

Two-stage concentrated sulfuric acid hydrolysis process

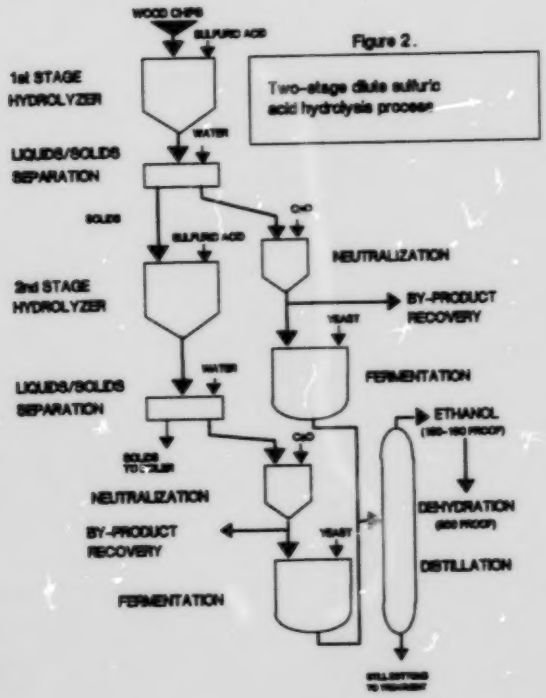

Figure 2.

Two-stage dilute sulfuric acid hydrolysis process

Economic evaluations of the two processes were conducted to determine base-case, first-year production and capital costs for commercial ethanol production facilities. This paper presents the results of these evaluations and examines the sensitivity of ethanol production costs to various internal and external factors.

RESULTS

Cost estimates were determined based on preliminary engineering analysis of the concentrated and dilute acid hydrolysis processes. Mass and energy balances, equipment specifications, raw material, and utility requirements were determined. Based on these estimates, capital and production costs were prepared for ethanol-from-corn stover and ethanol-from-wood facilities using concentrated and dilute acid hydrolysis, respectively. Capital and production costs for the two facilities are given in Tables 1 and 2. Each plant was designed to process 500 tons per day of feedstock. Capital costs are given by plant section and include the following areas where applicable: feedstock handling, hydrolysis, neutralization, furfural and acetic acid recovery, C_6 fermentation, C_5 fermentation, distillation, waste treatment utilities, and offsites. Capital costs for these sections are based on actual vendor quotes received for the major equipment items. Site preparation, engineering, architectural costs, contractor fees, contingency, and working capital have been included to give total capital investments of $56.5 million and $81 million for the concentrated and dilute acid hydrolysis facilities, respectively.

Table 1: Total Capital Investment for 500 t/d Concentrated and Dilute Acid Hydrolysis Facilities

Plant Section	Capital Investment: Concentrated Acid Hydrolysis Facility	Capital Investment: Dilute Acid Hydrolysis Facility
Feedstock Handling	1,597,000	10,240,000
Hydrolysis	13,418,000	15,194,000
Neutralization	1,794,000	875,000
Furfural and Acetic Acid Recovery	-	12,447,000
C_6 Fermentation	8,744,000	7,996,000
C_5 Fermentation	11,969,000	11,534,000
Distillation	3,261,000	5,466,000
Waste Treatment	5,492,000	5,857,000
Utilities	4,892,000	5,662,000
Offsites	5,312,000	5,621,000
Total	56,479,000	80,838,000

Table 2: Production Cost Estimate - 500 t/d Concentrated and Dilute Acid Hydrolysis Facilities

	Production Cost ($/gal)	
	Concentrated Acid Hydrolysis	Dilute Acid Hydrolysis
Raw Materials		
Feedstock	$0.33	$0.38
Acid	0.27	0.04
Lime	0.15	0.02
Chemicals	0.12	0.09
Utilities	0.05	0.05
Labor	0.19	0.25
Overhead and Maintenance	0.17	0.54
Waste Disposal	0.03	—
By-Products		
Electricity	(0.21)	(0.20)
Furfural	—	(0.16)
Acetic Acid	—	(0.16)
Annual Operating Cost	1.10	0.85
Capital Charges	0.59	0.96
Ethanol Production Cost	$1.69	$1.81

Production costs are based on the production of 12.5 million gallons of ethanol from the concentrated acid hydrolysis facility and 11 million gallons from the dilute acid hydrolysis facility. Both processes include a credit for the sale of excess electricity. Production costs for the dilute acid hydrolysis facility also include credits for by-product furfural and acetic acid. Capital charges were estimated to be about 13% of the total capital investment. Based on these determinations, production costs were calculated to be $1.69 and $1.81 per ethanol gallon for the concentrated and dilute acid hydrolysis processes, respectively. All costs are given in 1988 dollars.

DISCUSSION

Base-case capital and production cost estimates for the two acid hydrolysis facilities do not include the potential economic effect of process improvement research currently being conducted at TVA. TVA has identified several internal and external factors that may reduce ethanol production costs. These factors are: (1) acid recovery, (2) increased fermentation efficiency, (3) production of furfural as a coproduct, and (4) integration of ethanol production systems with other industries. The potential economic effect of these factors on ethanol production price will be discussed.

Acid Recovery

The base-case concentrated acid hydrolysis design assumes no recovery of sulfuric acid. Research indicates that the potential does exist to efficiently recover a substantial amount of acid for recycle to the process (Moore and Barrier, 1987). Acid recovery research is being conducted to determine the potential of using solvent extraction, adsorption, or ion exclusion for the recovery of sulfuric acid in the TVA concentrated process. The amount of acid used in the dilute process is so small that acid recovery would not be economically feasible.

Capital and production costs have been determined based on the incorporation of each of these technologies into the current base-case design. Capital costs for the solvent extraction process were calculated to be $4.2 million. Production costs for the process are based on the recovery and recycle of 93.2% of the sulfuric acid used. Ethanol production costs were calculated to be $1.33 per gallon, a savings of about 36 cents per gallon over the base-case design.

Capital costs for the adsorption process are estimated to be $5 million. Ethanol production costs, based on the recovery of 30% of the acid used in the process, were calculated to be $1.61 per gallon, a savings of 8 cents per gallon over the base-case design.

Total capital investment for the ion exclusion process was calculated to be $5.3 million. The unit is designed to recover 95% of the acid used in the process. Based on these assumptions, ethanol production costs were estimated to be $1.31 per gallon when ion exclusion is incorporated into the base-case design.

Fermentation

Research is being conducted to identify methods to improve fermentation of corn and wood stover sugars to ethanol. In the base-case concentrated and dilute acid hydrolysis facility designs, xylose fermentation efficiency has been conservatively set at 50%, although yields of 70% have been achieved in laboratory studies (Moore and Barrier, 1987).

The sensitivity of ethanol production costs to improvements in five-carbon fermentation efficiencies were evaluated. A yield efficiency increase from 50% (used in base-case design) to 70% will reduce the cost of ethanol production by about 21 cents per gallon in both the dilute and concentrated acid processes. This increase assumes no additional processing or capital costs are incurred.

Furfural Production

The TVA dilute acid hydrolysis process base-case is designed to maximize ethanol yield. During processing, 23.7 pounds of by-product furfural per ton of hardwood is also produced. Even though the amount of furfural produced in the base-case is small, a credit of about 16 cents per gallon of ethanol produced is provided to the process based on a furfural market price of 50 cents per pound (Lambert et al., 1989).

If the five-carbon sugars were used to produce furfural (rather than ethanol), 181 pounds of furfural could be produced and recovered per ton of hardwood processed (assuming the furfural yield is 60% of theoretical which is 0.73 pounds of furfural

per pound of xylose). Substitution of five-carbon fermentation production facilities with a furfural facility would reduce capital costs from $80.8 million to $72.6 million. The combination of higher revenue and lower capital cost is equivalent to reducing ethanol production costs to 73 cents per gallon.

Furfural is a by-product that can also be produced from the xylose sugar that remains in the stillage from the concentrated acid process. In the base-case scheme, the unfermented xylose (50% of initial amount) in the stillage is submitted to evaporation and burned along with the other organics. If this xylose were used to produce furfural (rather than burned), 88 pounds of furfural could be produced per ton of feedstock processed. If furfural is sold for 50 cents per pound, a credit of about 52 cents per gallon of ethanol produced would result. The ethanol production costs would be reduced to $1.17 per gallon by the production of 88 pounds of furfural per ton of corn stover.

System Integration

The economic feasibility of ethanol-from-cellulose technology can be improved by integrating existing industrial facilities with biomass processing facilities. Often, construction and financing costs and other problems can be minimized by using facilities that already exist. Substantial cost savings can occur by sharing management, maintenance, and capital equipment. For example, cellulose-to-ethanol processing can be integrated with pulp and paper production. Since papermill sludge is high in cellulose, the use of this waste product could eliminate feedstock costs and reduce ethanol by 38 cents per gallon using the dilute acid process. In addition, waste disposal costs for the facility's "waste product" would be eliminated or significantly reduced. Integration with other wood processing, municipal solid waste separation and recycling, ethanol production, and agricultural processing industries is also possible.

CONCLUSIONS

Production of ethanol from cellulosic feedstocks can be achieved using either dilute or concentrated acid hydrolysis. The potential for commercialization of these technologies depends upon the successful development of methods which either improve the efficiency of the processes or maximize the production of coproducts.

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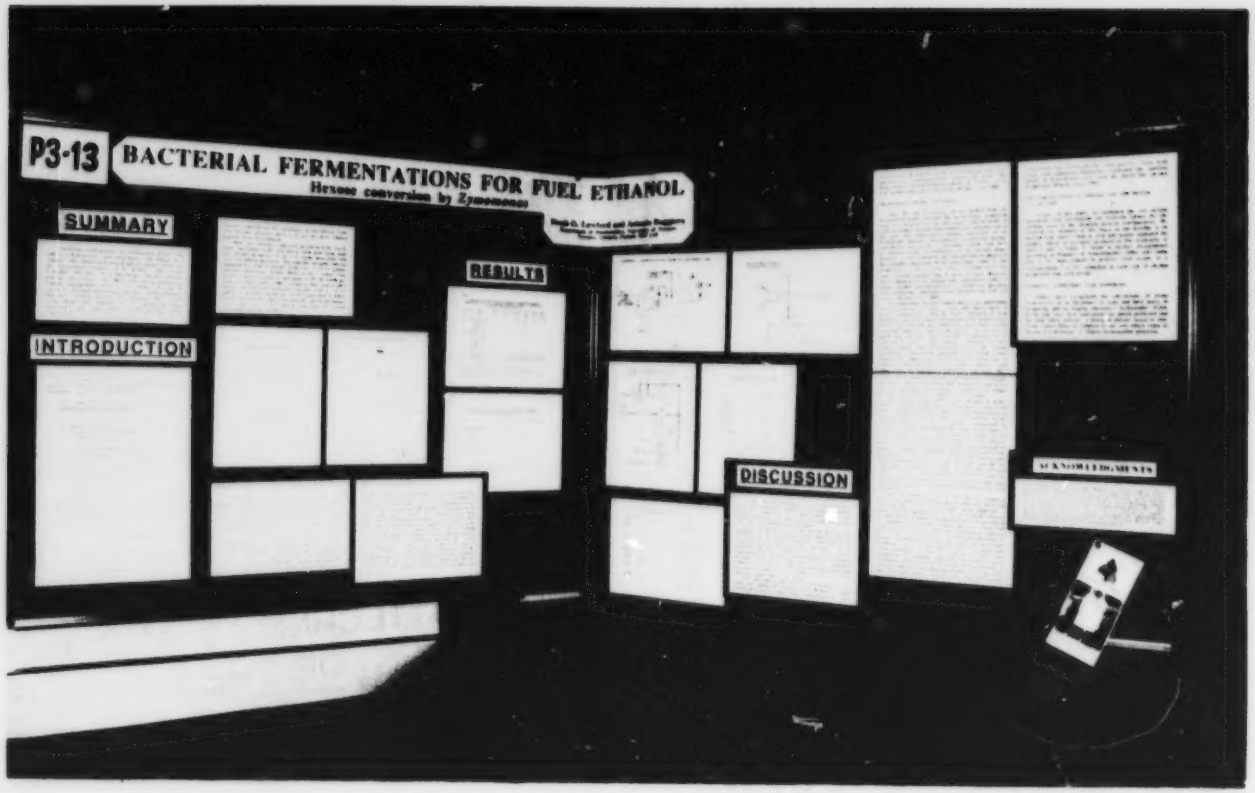
P3-13
BACTERIAL FERMENTATIONS FOR FUEL ETHANOL
Hexose conversion by Zymomonas
SUMMARY
INTRODUCTION
RESULTS
DISCUSSION

BACTERIAL FERMENTATIONS FOR FUEL ETHANOL
Hexose conversion by *Zymomonas*

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Biotechnology in the fuel alcohol industry relates to the various bioengineering strategies for improving the fermentation process with respect to the efficiency of substrate to product conversion (yield), final product concentration and productivity. These are considered to be the three most important factors arising out of cost sensitivity analyses for motor fuel alcohol production by fermentation and can be used as criteria in assessing process (fermentation) performance with a view to improving efficiency through a combination of both biological and engineering strategies. Compared to chemical processes, fermentation is generally considered a low productivity and capital intensive approach to producing organic chemicals. For example, the productivity associated with the production of industrial alcohol (ethanol) by the hydration of ethylene is about 40 times the productivity of traditional batch fermentations using yeast. Over the last couple of decades there has been extensive biochemical engineering research into improving the productivity of alcohol fermentations. The engineering approach to improving process productivity has involved operating the fermentors continuously at higher cell densities with systems employing cell retention (immobilization) or cell recycle. The biological approach to process improvement addresses the characteristics of the bio-catalyst and it is now generally recognized that substitution of yeast by the highly ethanologenic bacterium *Zymomonas* results in improvements to both yield and productivity.

Recent studies have involved comparative performance assessments of different genotypic (alcohol tolerant) and phenotypic variants of *Zymomonas* in continuous fermentations using feedstocks from a commercial corn wet-milling operation. In these studies, starch hydrolysis was effected either by thermochemical (high temp/plug-flow acid convertor) or enzymatic processing. *Zymomonas* has been shown to maintain its superior kinetic and yield properties in systems comprised of steep water (as sole source of nutrients) and where Zymo-stillage was used as back set. Our study has also involved a systematic examination of the effect of pH and other potentially toxic components of the fermentation system (eg. lactic acid and calcium). The superior kinetic properties of *Zymomonas* can be exploited to effect a 2-5 fold improvement in volumetric productivity. With feedstock accounting for about 70% of production costs, a 5-10% improvement in yield with *Zymomonas* represents a significant process improvement. With a 7% loss of starch in wet-mill processing and 97% saccharification efficiency, a tonne of corn (15% moisture, 60% starch) yields about 340L ethanol by yeast processing and about 380L using *Zymomonas*.

Dans l'industrie des alcools combustibles, la biotechnologie consiste à appliquer diverses stratégies visant à améliorer la méthode de fermentation en ce qui concerne l'efficacité de la transformation du substrat en produit (rendement), la conentration du produit final et la productivité. Ces trois facteurs sont considérés comme étant les plus importants d'après des analyses de sensibilité des coûts portant sur la production, par fermentation, d'alcool destiné à être utilisé comme carburant à moteur et ils peuvent servir de critères pour l'évaluation de la performance du procédé (fermentation) qui vise à améliorer l'efficacité, grâce à une combiason de stratégies biologiques et techniques. Comparativement au procédé chimique, la fermentation est généralement considérée comme présentant ine faible productivité et comme une approche coûteuse à la préparation de produits chimiques organiques. Par exemple, la productivité de la méthode consistant à hydrater de l'éthylène pour obtenir de l'alcool industriel (éthanol) est à peu près 40 fois plus élevée que celle des fermentations discontinues traditionelles effectuées à l'aide de levures. Depuis au moins deux décennies, des recherches intensives en génie biochimique ont porté sur l'amélioration de la productivité des fermentations visant à former de l'alcool. L'approche technique visant à améliorer la productivité de la méthode a consisté à exploiter des fermenteurs en continu, en présence de densité de cellules supérieures, avec des systèmes faisant appel à la rètention des cellules (immobilisation) ou au recyclage des cellules. L'approche biologique visant à améliorer la méthode porte sur les caractéristiques du bio-catalyseur et on reconnaît maintenant, en général, que la remplacement de la levure par la bactérie très productrice d'éthanol qu'est *Zymomonas* donne lieu à des améliorations de rendement et de la productivité.

Des études récentes comportaient des évaluations comparatives de variants de *Zymomonas* présentant différents caractères génotypiques (tolérance à l'égard de l'alcool) et phénotypiques, réalisées au cours de fermentations continues à l'aide de matières de base obtenues auprès d'une exploitation commerciale de broyage du mais à l'état humide. D'aprés les résultats de ces travaux, l'hydrolyse del'amidon était touchée soit par le traitement thermochimique (convertisseur acide à haute temp. et à écoulement en blocs), soit par le traitement enzymatique. On a montré que *Zymomonas* conservait ses propriétés cinétiques et son rendement supérieurs dans des systèmes constitués d'eau de macération (seule source d'éléments nutritifs). Notre étude comportait également un examen systématique de l'effet du pH et d'autres composants potentiellement toxiques du système de fermentation (par ex. l'acide lactique et la calcium). Il est possible d'utliser les propriétés cinétiques supérieures de *Zymomonas* pour obtenir une productivité volumétrique deux à cinq fois plus élevée. Compte tenu du fait que les matières de départ représentent environ 70% des coûts de production, une augmentation de 5-10% du rendement avec *Zymomonas* constitue une importante amélioration du procédé. Si l'on prend en compte une perte d'amidon de 7% dans le cas du traitement par broyage à l'état humide et une efficacité de 97% pour la saccharification, on prévoit obtenir, à partir d'une tonne de mais 15% d'humidité, 60% d'amidon), environ 340L d'éthanol avec le traitement aux levures et environ 380L d'éthanol avec *Zymomonas*.

INTRODUCTION

Fermentation fuel alcohol - an historical perspective

History will no doubt record that the impetus for our interest in bioenergy, and in particular, our interest in fermentation ethyl alcohol as an alternative to non-renewable fossil fuels, came from the so-called *energy crisis* of the 1970s. To a large extent, our introduction to energy conservation was born out of the prophetic statements of the preceeding decade about the rapidly dwinding supply and possible exhaustion of petroleum in the Middle East. Oil prices had skyrocketed and the economics of producing alternative fuels from renewable resources looked favourable. In the U.S., the Carter administration poured billions of dollars into supporting the "gasohol" program, energy conservation and efforts to achieve energy self sufficiency. There were substantial government subsidies associated with denatured fermentation alcohol destined for use as a gasoline extender in 10% blends. In attempting to become energy self-sufficient, Brazil implemented an ambitious program (called Proalcool) aimed at replacing a major portion of its gasoline requirements by fermentation alcohol. The idea of using ethanol as an automotive fuel is not new. Gasoline/ethanol blends were commonly used in Europe prior to World War II when the cost of petroleum favoured the economics of fermentation ethanol production. Brazil now produces about 4 billion gallons of ethanol annually and most of the automobiles are designed to run on "neat" alcohol fuel. Only about 4% of this fermentation ethanol in Brazil is destined for the chemical industries as a feedstock in the production of ethylene, acetaldehyde, acetic acid, etc. By comparison, the U.S. produces just over 900 million gallons of ethanol (C&EN *News*, March issue, 1989)

Ethanol - as an octane enhancer and an "environment-friendly" fuel

The OPEC oil cartel, that once held the world over the barrel, has eased the restrictions on supply so that now the much lower price of crude no longer makes fuel ethanol the economic proposition that it once appeared to be. It is probably true to say that the fuel alcohol industry only survives today because of government subsidies and tax incentive programs. However, the interest in fuel ethanol surprisingly persists. Today, largely because of environmental concerns related to air quality, toxic emissions including the use of lead in gasoline, global warming due to increasing levels of carbon dioxide from the use of non renewable fuels, ethanol continues to be in vogue. Ethanol is not sold now as a gasoline extender but instead is being marketed as "ethyl additive" or the "octane booster" in lead-free gasoline. There is an EPA mandated oxy-fuels program in the U.S. which is designed to improve the air quality in certain non-attainment areas such as Colorado. In North America leaded gasoline is being legislatively phased out. Fermentation ethanol is now being called "bioethanol", an environment-friendly fuel that utilizes recycled carbon, as opposed to petroleum derived industrial ethanol which is a non renewable source of energy that has a net positive effect on the amount of carbon dioxide in the atmosphere thereby contributing to global warming and the so-called *greenhouse effect*.

The present economic outlook and the need for innovation

Economic analyses made when the costs for fossil fuels were relatively high, back in the 1970's, indicating that fermentation ethanol might be able to compete with ethylene-derived ethanol, are no longer valid and the present economic environment, with the price of crude at less than $20US/barrel, provides the necessary incentive for developing new and more efficient fermentation processes.

The economics of the fuel alcohol industry are undoubtedly complex; for example, it is slowly being recognized that there will be a price to pay for improved air quality. Apart from the ever changing price of oil, there are a number of important contributing factors in determining profitability for fuel alcohol. The surviving and more successful fuel alcohol plants are not only relatively large in scale but are also integrated with existing industrial operations so that they are well positioned to take advantage of utility synergisms and co-product utilization. It is already apparent that survival in the fuel alcohol industry will require flexibility with respect to feedstock capability for cost effective production of fuel alcohol.

A logical first step in approaching the issue of process improvement is to decide which parameters in the overall process are the most economically sensitive so that specific improvements will impact positively through a reduction in production costs. Having concluded which factors require improvement, what remains is to design an appropriate strategy for implementing the desired improvement in the process, bearing in mind, wherever appropriate, the theoretical maximum value to be achieved for any given parameter (eg. yield).

Factors of techno-economic importance

Although the fuel alcohol industry has developed out of the technology-base of the alcoholic beverage industry, consumer acceptability of the product with respect to "taste" is not a constraint to improving process efficiency in production of fuel alcohol. The three most important factors arising out of cost sensitivity analyses for motor fuel alcohol production by fermentation are shown in the Table below.

FACTORS OF TECHNO-ECONOMIC IMPORTANCE IN ASSESSING ETHANOL FERMENTATION PROCESSES

1. **PRODUCT YIELD**
   the efficiency of converting the feedstock to ethanol
2. **VOLUMETRIC PRODUCTIVITY**
   the amt. ethanol / unit volume / unit time
3. **FINAL PRODUCT CONCENTRATION**
   the conc'n of ethanol exiting from fermentation system

As a direct consequence of the cost of raw materials, by far the most important of these factors is the yield. These factors have been adopted as our criteria in assessing process (fermentation) performance with a view to improving efficiency.

Our strategy for designing a better fermentation process

The strategy that we adopted for designing a better fermentation process was to take advantage of the modern advances in biotechnology and bioengineering to achieve a state-of-the-art, economically competitive process for fuel alcohol production.

PRODUCTIVITY - a look at the prior art

Fermentation is generally considered a low productivity and capital intensive approach to producing organic chemicals. For example, the productivity associated with the production of industrial alcohol (ethanol) by the hydration of ethylene is about 80 Kg EtOH/m^3/hr compared to the production of bioethanol in batch fermentations using yeast, where the productivity is only about 2 Kg EtOH/m^3/hr. This is a particularly relevant comparision in light of the fact that most of the world's supply of fermentation ethanol is still produced by the time-honoured tradition of batch fermentations using yeast.

Historically, one of the first approaches to process improvement has involved attempts to increase productivity. From an engineering perspective this can be achieved quite simply by operating the fermentors in a continuous mode rather than the more traditional "fill and empty" or batch mode. There has been a gradual adoption within the industry of *continuous* operation which, in itself, is viewed as a step forward in process improvement. Apart from being less labour intensive and apart from the benefits which accrue in terms of improved productivity, continuous operation offers ease of control and does not impose peak loads on up- and downstream processing equipment.

The consequence of converting from batch to continuous flow fermentations is a three fold increase in productivity from about 2 to 6 Kg EtOH/m^3/hr. Operating continuously at higher cell densities using continuous cell recycle reactors was another effective means of greatly increasing the productivity. A continuous flow fermentor which is operated so as to retain the yeast cells, usually by some type of external cell harvesting device (centrifuge or settling tank) in which the cell density would be consequently relatively high (50-80 g DW yeast/L) has an ethanol productivity of 30-40 Kg EtOH/m^3/hr. There are several different technologies relating to cell recycle or cell retention (eg. flocculation or cell immobilization by entrapment or adsorption, biofilm reactors, etc.) that have been described both in the scientific and patent literature.

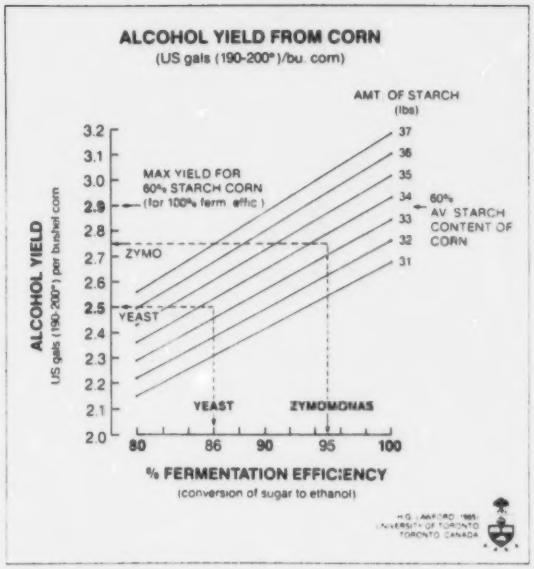
A literature survey clearly reveals that the majority of process improvements reported by others have focussed on this type of engineering strategy for increasing the productivity of ethanol fermentations.

YIELD and the efficiency of converting sugar to ethanol

While reactor productivity is an important aspect of the economics of fermentation ethanol, it is not the most important. The major variable affecting process economics is the cost of the raw material. This makes the selection of the feedstock a very important economic consideration and focusses attention on the importance of maximizing yield - where a 1% increase in yield can mean as much as 700,000 extra gallons (US) of undenatured absolute alcohol per year based on the same rate of feedstock utilization for a high-capcity production plant. It follows that economic operation requires almost complete conversion of available fermentable sugars to alcohol. The obvious objective here is to get the most ethanol possible from the feedstock.

The current practice of using sources of carbohydrate such as cereal grains that can be used alternatively as either food or feed, means that there is a competition for feedstocks between the food and fuel industries, the consequence of which is that the fermentation feedstocks can account for as much as two-thirds of the cost of producing ethanol. Furthermore, production costs are obligatorily coupled to the seasonal variations in grain prices and availability. Clearly, there is a need to produce fuel alcohol from cheaper feedstocks such as agricultural or municipal lignocellulosic residues that are without food value. However, traditional yeast cultures are only able to utilize a fraction of the total available sugars from these raw materials. Hence, there has been an interest in new fermentations and the search for alternative and different microorganisms capable of using lignocellulosic feedstocks.

Most fuel ethanol is currently produced from starch, more specifically from corn starch, with most large scale fuel alcohol producers in the U.S. being associated with corn wet-milling operations. The generally accepted industry standard for yield of ethanol from corn is 2.5 US gallons absolute ethanol per bushel (56lbs) of No. 2 yellow corn, which in metric measure is equivalent to 371.5L EtOH per tonne of corn (USDA, 1980). When considering various strategies directed towards yield improvement, it is worthwhile to do so with a knowledge of the theoretical maximum yield which can be calculated assuming 100% process efficiency with respect to the individual unit operations, namely saccharification, fermentation and distillation (product recovery). Assuming that corn is 60% starch, the maximum alcohol yield is 2.9 US gallons of absolute ethanol per bushel (equivalent to 430 L EtOH/tonne of corn). Hence the generally quoted benchmark yield figure of 2.5 US gals/bu represents an overall processing efficiency of 86% .



The Figure above represents a graphic illustration of the potential for yield improvement in terms of the efficiency of the process microorganism in the conversion of fermentable sugar (glucose) to ethanol.

In addition to the saccharification process being less than 100% efficient, corn wet-milling operations usually experience about a 5% loss of the starch in the process upstream to saccharification. In order to achieve a yield of 2.5 gals/bu, the yeast would have to convert sugar to ethanol with an efficiency of greater than 90% and this does not correlate well with literature data for yeast fermentations. Yeast is known to operate at a much lower efficiency in the range 84 - 87%. However, more recent yield values from some of the recently up-graded and larger-scale fuel alcohol plants in the U.S., where the process is continuous and operated at high cell density with cell recycle, suggest that under these operating conditions, yeast might indeed be capable of achieving conversion efficiency higher than is customarily observed. As an alternative explanation to such an abnormally high conversion efficiency for yeast, one can suspect the calculation used to derive the generally quoted yield value of 2.5 gals/bu.

Yeast is not nature's only means of making alcohol.

Up to this point we have examined primarily engineering approaches to process improvement. Recalling that our strategy was to integrate advances in biotechnology and bioengineering, we also carefully explored possible biological opportunities for achieving our objective of designing an improved fermentation process for fuel ethanol production.

The biological approach to process improvement addresses the performance characteristics of the biocatalyst or process microorganism. Yeast is traditionally regarded as the bio-catalyst in ethanol fermentations and although most fuel alcohol fermentation processes currently utilize well known strains of brewer's or baker's yeast, recent research has focussed on the search for new varieties and alternative ethanologenic organisms tailored to the specific needs of the emergent fuel alcohol industry. Yeast is not nature's only means of making alcohol. The monopoly enjoyed by yeast is now being challenged by new alternative alcohol producing organisms. For over ten years we have been experimenting with a bacterium, called *Zymomonas*, whose superior kinetic and yield characteristics have the potential to revolutionize the fuel alcohol industry. Unlike yeast, the bacterial culture does not require small amounts of oxygen for growth and is therefore a more suitable candidate for continuous fermentations of the type required for economic production on an industrial scale. But what is so exciting about the bacterial fermentation is that it is both faster and much more efficient than yeast.

Specific objective of the present investigation

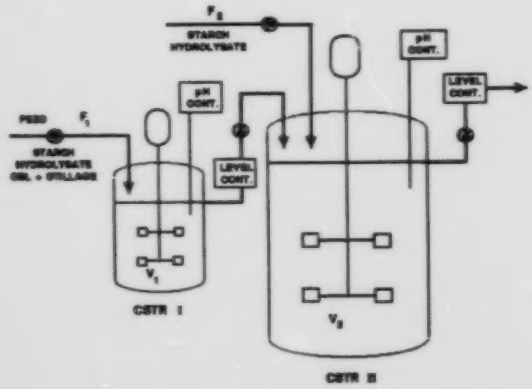
For the past ten years my lab has been investigating the potential of the ethanologenic, gram-negative bacterium, *Zymomonas*, as an effective and more efficient replacement of yeast in continuous ethanol fermentations. Whereas this familiarity is the basis for our continuing confidence in the future potential for *Zymomonas* in the fuel alcohol industry, the present study was undertaken primarily to provide evidence to counter the arguments of those not yet convinced by our previous data that had been generated using pure laboratory-grade chemical feedstocks. We wished to specifically address the concerns of those who feared that *Zymomonas* was too fragile or fastidious an organism to withstand the rigours of the industrial process environment. The present study focuses on the potential for yield improvement using an industrial feedstock (specifically enzymatically-hydrolyzed corn starch) in which all essential growth nutrients are supplied exclusively by the process water (corn steep liquor) from a corn wet-milling operation. We hoped to demonstrate the benefits accruing to a current commercial operation through the simple replacement of yeast with *Zymomonas*. However, because of certain limitations in the design configurations of the equipment employed (eg. operated without biomass retention or cell recycle), there was no attempt to demonstrate the full extent of the kinetic advantages of *Zymomonas* in improving productivity. In a separate collaborative study, we have made a direct side-by-side comparison of *Z. mobilis* with a commercial yeast strain on this same industrial feedstock, the results of which corroborated our claims regarding the superior yield and kinetic characteristics of the bacterial fermentation (Beavan *et al.*, 1989).

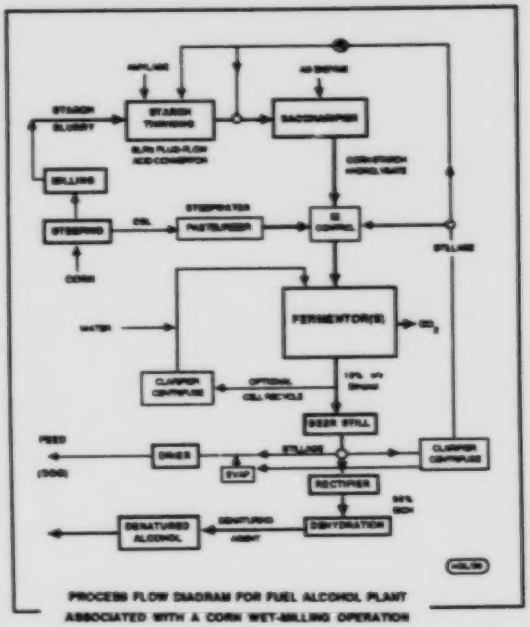
EQUIPMENT and PROCEDURES

Process organism: The type culture of *Zymomonas mobilis* ATCC 29191 was used throughout and was obtained from the American Type Culture Collection (Rockville, MD, USA). Stock cultures were maintained and inocula prepared as described previously (Lawford *et al.*, 1988).

Fermentation media and feedstock preparation: The feed to the fermentors was formulated to mimic that of a particular large scale fuel alcohol producer in the U.S. and contained approximately equal parts by volume of corn starch hydrolysate, corn steep liquor and stillage. Commercial feedstocks containing enzymatically hydrolysed corn starch from two local corn wet-milling operations were used (Cardinal and Port Colborne, Ontario). On average the hydrolysate was 90-92% glucose and assayed for D-glucose at 305 g/L. HPLC determinations showed about 4% DP2 and 6% DP3 in the hydrolysate. Starch hydrolysate was diluted to give appropriate dextrose equivalent (DE). In the two-stage experiments the hydrolysate was spiked with glucose to give a final DE of 340 g/L. Process yield (fermentations efficiency) determinations were based solely on glucose and not on total available carbohydrate in the fermentor feed. The corn steep liquor (CSL) was supplied by St. Lawrence Starch Co. Ltd. (Mississauga, Ont.). The stillage was prepared from spent *Zymomonas* fermentations by evaporating to 40% of its volume and diluting with tap water back to 80% of the original volume. The fermentor feed reservoirs were agitated.

Fermentation equipment: Continuous fermentations were conducted in 1L (CSTR I) and 2L (CSTR II) stirred bioreactors (New Brunswick Scientific Co., Edison, NJ, USA) with working volumes of 350ml and 1500ml respectively. Agitation was minimal. In order to achieve alcohol enrichment >6% (v/v), the two vessels were operated in series as shown in the diagram of the experimental apparatus. Both vessels were operated with pH, temperature and level control. The pH was maintained at 5 with alkali and the temperature was kept at 30°C.





RESULTS and DISCUSSION

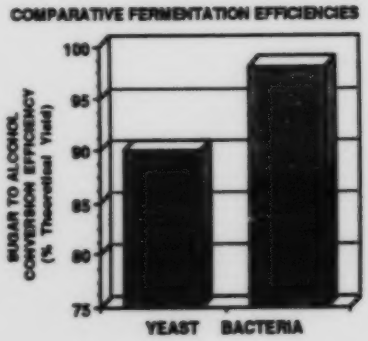
At first continuous fermentations were conducted with a single stirred bioreactor (CSTR I) using media formulations designed to mimic that of a typical feedstock in a fuel alcohol plant associated with a corn wet-milling operation. The results are summarized in the Table 1.

From these initial trials one can conclude that nutrients supplied in the process water (CSL with stillage as back set) are sufficient to sustain steady-state operation of the continuous fermentation in which *Zymomonas mobilis* replaced the more traditional yeast culture. These experiments also revealed an optimal glucose concentration of about 12.5% (w/v) for the feed to such a continuous culture of *Z. mobilis*. A similar observation had been made previously by both Lavers *et al.* (1981) and Lee *et al.* (1979) using lab-grade, glucose-salts media.

The only report in the literature of *Zymomonas* being used with commercial feedstock was at Pfeifer & Langen (Werk Dormagen, Germany) using enzyme hydrolyzed waste wheat starch (B fraction) in 50 m^3 bioreactors that were operated in a continuous mode without cell recycle. The final ethanol concentration was 56-60 g/L (7.1-7.6 vol.%) with productivities up to 4.5 g/L/hr (Bringer *et al.*, 1984).

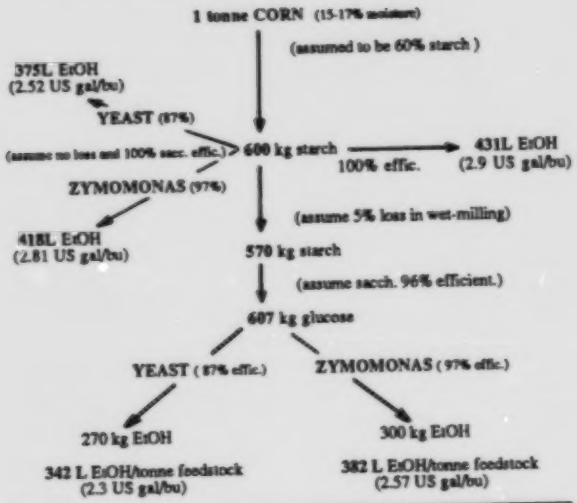
Higher yield using *Zymomonas* even with a commercial feedstock

Unlike yeast, which produces end-products other than ethanol (such as glycerol, organic acids and fusel oils), *Zymomonas* converts glucose almost exclusively to ethanol and carbon dioxide. Typical ranges of observed fermentation efficiencies for yeast and *Zymomonas* are compared graphically in the Figure below.



The bacterial fermentation exhibits an improvement in sugar to alcohol conversion efficiency of from 5 - 10% compared to yeast and this can translate to an extra one-quarter of a gallon (US) of absolute alcohol per bushel of corn processed (equivalent to an extra 37L EtOH/tonne). In addition, the absence of by-product higher alcohols and fusel oils, makes product recovery less complicated. An extra bonus is that, because glycerol is absent, the handling and drying of the residue solids (DDG) becomes easier.

Materials Balance Flowsheet
Fuel Alcohol from Corn Starch



Maximizing the alcohol concentration

Since the cost of recovery of the alcohol from the fermentation broth represents the second major production cost, it is necessary to use high sugar concentrations in order to produce maximal final ethanol concentrations but at the same time maintaining complete utilization of the fermentable substrate. However, at sugar feed concentrations in excess of about 12.5% (w/v), the system was unstable and oscillated with respect to ethanol concentration with about a 3 day periodicity. The maximum ethanol concentration that can be achieved with the single CSTR is about 8% (v/v) independent of whether it is operated with yeast or *Zymomonas*. This derives from the fact that yeast and *Zymomonas* are equally sensitive to the end-product of their metabolism, namely ethanol. It is this ethanol toxicity which causes growth to be inhibited. Since in an open-type continuous flow system, the process organism is obliged to grow at a rate that is at least as fast as the dilution rate, the maximum attainable ethanol concentration is determined by the upper limit of the ethanol tolerance of the process organism. However, this limitation in mixed bioreactors can be overcome to some extent by altering the design of the continuous flow bioreactor to one of plug-flow in which the contents of the reactor travel unidirectionally as discrete elements or "plugs". Plugged flow can be mimiced by having the flow course through a series or train of bioreactors. Theory predicts that a significant reduction in holding time over that required by a single vessel operation can be achieved using two or more fermenters in series.

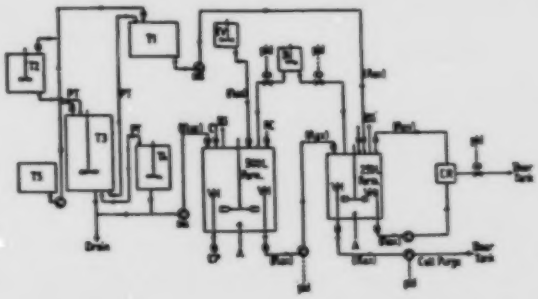
Our approach to achieving product enrichment was to use a two-stage system with beer enrichment being accomplished in the second stage; however, we were limited by the concentration of glucose in the available commercial starch hydrolysates (Table 2). The productivity of this two-stage system is comparatively low with a overall residence time of about 23 hours. However, this is identical to the holding time required to achieve a similar alcohol concentration in a commercial operation using multistage continuous yeast fermentation with cell recycle (Beavan *et al.*, 1989). At comparable cell mass loading there is an opportunity with *Zymomonas* for about a five fold improvement in process productivity. This has been confirmed in both laboratory and pilot plant fermentations with productivities in the range 120-200 Kg EtOH/m^3/hr. This ability of the bacterial culture to improve the kinetics of the process means that the same rate of alcohol production can be achieved in vessels of 20% capacity compared to yeast-based systems which dramatically lower the capital investment in fermentation equipment.The two-stage system exploits the capacity of *Zymomonas* for high rates of ethanol production under non-growing conditions (2nd stage) where the fermentation efficiency approaches 100% conversion of added fermentable carbohydrate to ethanol. The higher yield in the second stage fermentor is due to the fact that the non-growing bacterial culture is no longer diverting carbon for the synthesis of new cell mass.

The two-stage system (Table 2) was operated in steady-state for 25 days. Disturbances to the process seem to be mostly associated with the presence of lactic acid bacteria in the substrate feed. Lactic cultures are beneficial in the steeping process and are a common contaminant in contiguous alcohol fermentations. We observed that above a level of about 5% (w/v) lactic acid, the system was no longer stable and glucose would appear in the effluent. However, we have been thus far unsuccessful in attempts to mimic this apparent detrimental effect of lactic acid on the performance of *Zymomonas* in standard 10% glucose-salts media containing 5-10% (w/v) exogenous lactic acid. We are continuing to pursue this investigation of the effect of lactic culture infection on the performance of *Z.mobilis* but our observations to date suggest an involvement in some other (unidentified) product of metabolism produced by the lactic acid bacteria.

What evolved from many years of experimenting, first in the laboratory and later in the pilot plant, was the **ZymoGen System** - a high-performnce, continuous bacterial fermentation process for motor fuel alcohol production (Charley *et al.*, 1983). The patented, high-performance, **ZymoGen** process (H.G.Lawford, US Patents 4,647,534 and 4,731,329) is a continuous cascade system with propagation of *Zymomonas* in the first stage and product enrichment (12% vol.) in the absence of cell growth in subsequent stages and which can be operated with cell recycle for increased productivity. This novel, continuous bacterial fermentation process fulfills the economic criteria with respect to the three sensivity factors of yield, productivity and product concentration.

Shown below is a schematic repreaentation of the design chosen to increase the productivity of the overall process. A two-stage design permits optimization of product formation in both growth and non-growth environments and allows full exploitation of the unique capacity of *Zymomonas* for relative high rates of ethanol production when not growing. By employing cell recycle to the 2nd stage, the overall residence time was reduced by about 70% .

Design of Bio-Hoi Developments' Pilot Plant Fermentation Unit
(not to scale)



Legend:

IV	- Inoculum development vessel	A	- Aeration facility
B	- Base vessel	VH	- Variable height standpipe
	- Transfer pump	BG	- Exhaust gas
ms	- Manual set	CR	- Cell recycle device
pid	- PID control	I	- Inoculation port
(flex)	Flexible line	CT	- Cell transfer port
	- Quick connect fitting	RC	- Recycle port
	- Control valve	CP	- Cell purge facility
PT	- Pressure transfer		

In addition to developing the multistage *ZymoGen* system, other high-performance processes using phenotypic and genoptypic variants of *Zymomonas* have been explored over the course of our investigations with this alternative alcohol producing organism. For example, flocculating mutants of *Zymomonas* have been developed for use in a continuous process exhibiting a five fold increase in volumetric productivity at a concentration of 8% (vol). The residence time in this process is about 1 hour (Fein *et al.*, 1983) When the fermentor is operated with cell recycle, the residence time can be reduced to only 18 minutes (Fein *et al.*, 1983)

As an alternative to process improvement through genetic manipulation, we have pioneered a physiological approach to increasing the performance of *Zymomonas* through manipulation and control of the physical and chemical environment (Lawford & Stevnsborg, 1987). We have discovered how to alter the chemical and physical environment in such a way as to beneficially affect the metabolism of organism. Energetically "uncoupled" phenotypes with markedly increased specificic rates of ethanol production have been generated under conditions of certain nutritional limitations in continuous fermentations (Lawford, 1988; Lawford *et al.*, 1988). This strategy for process improvement is the subject of several patents that issued in 1989 (H.G.Lawford: US 4,816,399; US 4,808,526, US 4,808,527, US 4,812,410) with one application still pending in the United States.

There are however, some areas for further R&D and these are (i) broadening the carbohydrate utilization profile of *Zymomonas* beyond glucose and sucrose, (ii) improving the ethanol, temperature and salt tolerance of the organism, and (iii) assessing nutritional aspects of DDG with *Zymomonas* instead of yeast for animal feed (eg. vitamin content, etc.). Finally, although theoretically there should be no more heat generated in a bacterial fermentation, because of the greater activity in the case of bacterial systems, it will be necessary to engineer efficient means for heat transfer in the proposed systems especially at high cell mass loadings with relatively high rates of fermentation.

Last year we successfully completed a series of field trials at one of the largest fuel alcohol producers in the USA. In direct side-by-side comparisons of commercial yeast and *Zymomonas* in a corn wet-milling operation using hydrolyzed corn starch with all necessary nutrients being provided by the corn steep water and recycled process stillage, the bacterial system consistently out performed the yeast process. These field trials with industrial feedstocks confirmed the superior nature of *Zymomonas* over yeast for motor fuel alcohol production (Beavan *et al.*, 1989)

The ecomonic benefit of replacing yeast with bacteria - a case study

As part of our field trials at one of the largest fuel alcohol producers in the U.S., we estimated the cost savings associated with substituting our bacterial culture for the existing yeast in the identical process configuration. We focussed our attention in this study on the benefits to be derived from improvement in yield and largely neglected the positive effects of increased productivity. There would be no increase in raw materials requirements. Since there is no increase in processing costs upstream from the fermentors, the only added processing costs are for the downstream handling of the extra ethanol and carbon dioxide that would be produced as a consequence of the increase in yield. This extra cost has been estimated to be about $8,000.per million gallons of ethanol. Our fermentation trials at the plant clearly demonstrated that the bacterial culture operates effectively and more efficiently with the same feedstock as yeast. Furthermore, it has been estimated that the costs for retrofitting the existing facility (which currently operates in a continuous multistage mode with cell recycle), from yeast to the *ZymoGen* system, would be negligible.

It was estimated that at the present grind rate of about 28 million bushels of corn per year, replacement of their yeast with *Zymomonas* would yield between an extra 3.4 to 7.6 million gallons of undenatured absolute ethanol depending on the particular operating conditions and the respective predictable fermentation efficiency of the bacterial culture (Table 3). The economics of cases 2 and 3 (Table 3) would be further strengthened according to Flannery & Steinschneider (1983) who claim that a 5% improvement in process yield results in a corresponding 2 to 3% reduction in total cost of alcohol production from corn starch.

Competitive technologies using *Zymomonas*

Others have recognized the advantages of using *Zymomonas* as an alternative to yeast and have active in promoting and developing alternative technologies (Table 4). In some cases these innovations are patent protected and the table below indicates a listing of patents issued to date in the United States in addition to our own which relate to the use of *Zymomonas* in ethanol fermentation processes.

In the U.S., American Eagle Fuels (jointly owned by Biocom of Atlanta, GA and Ethanol Authority Development Board of Nebraska) has been actively promoting their bacterial fermentation technologies which were developed by Dr. Horst Doelle and his associates at the University of Queensland (Australia). These processes are called the "Sucrotech Process" and "Glucotech Process" for fermentations based respectively on molasses (sucrose) or starch hydrolysates. However, patents have not issued in the U.S. in respect of either of these processes and it is not clear that the Glucotech Process does not infringe patents already issued and pending.

Dr. Peter Rogers and his research associates (University of New South Wales, Australia) have also been active in developing *Zymomonas*-based technologies with patents which claim improved performance by specialized strains which are surported to be more alcohol tolerant (US 4,403,034 and 4,443,543). However, our published research clearly demonstrates an inability to practice Rogers' invention and consequently brings into question the utility of employing Rogers' mutant cultures for increased alcohol concentration and the validity of the attending patent claims. (Stevnsborg & Lawford, 1986; Lawford & Stevnsborg, 1987)

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Table 1

SUMMARY OF SINGLE-STAGE CONTINUOUS BACTERIAL ETHANOL FERMENTATIONS USING STARCH HYDROLYSATE FROM A COMMERCIAL CORN WET-MILLING OPERATION

REACTOR CONFIG.	MEDIUM COMP.	DILUTION RATE (1/hr)	RESID. GLU (g/L)	ETHANOL CONC'N (Vol %)	YIELD $Y_{p/s}$ (g/g)	FERM. EFFIC. (%)	VOL. PROD. (g/L/hr)
CSTR I	Starch hydrolysate (DE =150 g/L) + "Zymo salts" with 0.5% YE (pH 5.5)	0.25	7.5	8.0	0.45	88	15.8
CSTR I	Starch hydrolysate (DE = 112 g/L) 10% CSL + 1.6 g/L NH_4CL + vitamins + citrate (pH 5.0)	0.20	0.3	6.7	0.47	92	10.8
CSTR I	Starch hydrolysate (DE = 129 g/L)	0.11	3.0	7.9	0.49	96	6.82
	30% CSL (filter sterilized) (pH 5)	0.15	11.7	6.9	0.46	90	8.10
CSTR I	Starch hydrolysate (DE = 204 g/L) 30% CSL (filter sterilized) (pH 5)	0.10	* system was unstable and never attained steady-state - observed oscillations with about a 3 day periodicity between max. ethanol conc'n of 8.3% and min. of 2.2% (vol).				

Table 2

SUMMARY OF TWO-STAGE CONTINUOUS BACTERIAL ETHANOL FERMENTATIONS USING STARCH HYDROLYSATE FROM A COMMERCIAL CORN WET-MILLING OPERATION

REACTOR CONFIG.	MEDIUM COMP.	DILUTION RATE (1/hr)	RESID. GLU (g/L)	ETHANOL CONC'N (Vol %)	YIELD $Y_{p/s}$ (g/g)	FERM. EFFIC. (%)	VOL. PROD. (g/L/hr)
Two-Stage Cascade System CSTRs connected in series							
1st stage CSTR I	Starch hydrolysate/glu (DE = 120 g/L) 30% vol CSL 35% Zymo stillage (pH 5.0)	0.16	2.5	7.2	0.47	92	9.0
2nd stage CSTR II	Starch hydrolysate/glu (DE = 340 g/L) pH 5.0	0.053	-	11.7	0.49	96	4.9
Overall System		0.043	-	11.7			4.0

Note: The volumetric rate of glucose consumption by this two-stage system is 8 g glu/L/hr with that of CSTR II being 5.44 g glu/L/hr. The holding time for biomass in CSTR II is (V_2/F_1) about 27 hrs.
The total time requiredto produce the approx. 12% beer is 23.3 hrs.

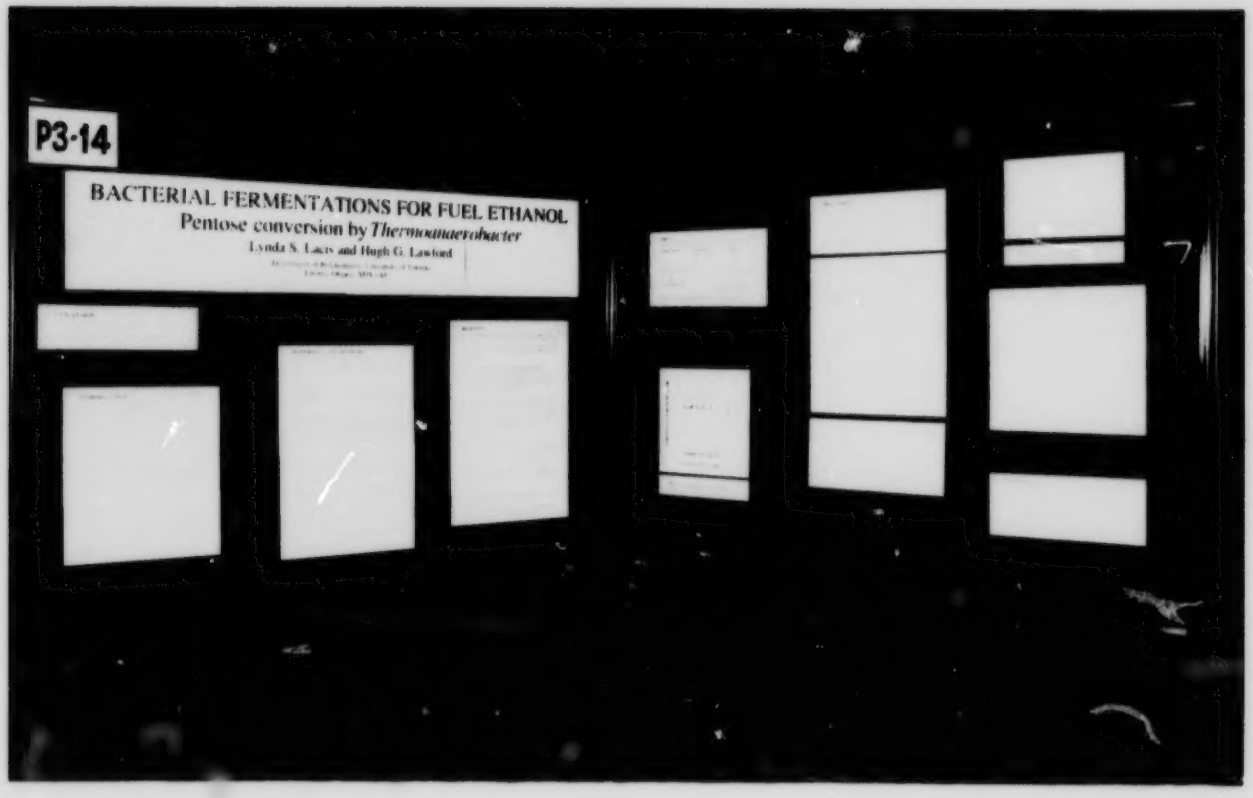
Table 3 ESTIMATED COST SAVINGS IN SWITCHING FROM YEAST TO BACTERIAL PROCESS

CASE	1	2	3
Organism	Yeast	Bacteria	Bacteria
Grind Rate Corn (bu/yr)	28,230,000	28,230,000	28,230,000
Process Yield (wt EtOH/wt sugar)	0.44	0.47	0.49
Fermentation Efficiency (%)	86%	92%	96%
Ethanol Production (US gal/yr)	70,000,000	73,400,000	77,600,000
Increase in EtOH	base case	3,400,000	7,600,000
Increase in CO_2 (tons)		10,600	23,800
Increase in revenue US$/yr @ $1.10/gal	-	$ 3,740,000.	$ 8,360,000.
Capital Cost	base case	$ 330,000.	$ 500,000.
Added Expenses ($/yr)	-	$ 33,000.	$ 50,000.
Increased Profits	base case	$ 3,707,000.	$ 8,310,000.

US fuel alcohol plant at 1989 operating capacity of 70 million gallons ethanol and averaging 2.49 US gal/bu corn. Capital cost represents heat exchangers, pump impellers and piping and arises from the extra heat generated by the more active bacterial culture during fermentation but assuming that increases in operating costs (ie. water and electrical) due to this extra heat are negligible.
Expenses are based on 10 year straight line of depreciation of capital investment. No credit is given for extra carbon dioxide produced in bacterial fermentation.

Table 4 US PATENTS PERTAINING TO *Zymomonas* TECHNOLOGIES FOR ETHANOL PRODUCTION

Note: USPO only FILING DATE	INVENTOR	ASSIGNEE	ISSUED	TECHNOLOGY
4,647,534 Sept. 1980	Lawford	Weston	Mar. 1987	The *ZymoGen* Process Two-stage, continuous process with high alcohol
4,731,329	Lawford	Weston	Mar. 1988	*CIPs filed to cover all Zymo
1,403,034 Mar. 1981	Rogers	Unisearch	Sept. 1983	Batch/Continuous processes Strains CP4 (ATCC 31821) strain ZM481 (ATCC 31823) specifies minimum specific rates for alcohol production and [P] - batch/continuous
4,443,544 Mar. 1981	Rogers	Unisearch	Apr. 1984	Single stage with recycle Claims "Zymomonas" (all strains)
4,443,543 Dec. 1981	Rogers	Unisearch	Apr. 1984	Flocculant strain ATCC 31822 (derived from ATCC 31821)
4,407,954 Dec. 1981	Clyde	-	Oct. 1983	"Fiber Fermenter " - uses immobilized Zymomonas (all strains) or other organisms continuation of Pat. 4,351,905
4,413,058 Jan. 1982	Arcuri	USDOE	Nov. 1983	strain specific "I" (NRRL B-12526) continuous with specific flocc. strain derived from ATCC 10988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BACTERIAL FERMENTATIONS FOR FUEL ETHANOL
Pentose conversion by *Thermoanaerobacter*
Lynda S. Lacis and Hugh G. Lawford

BACTERIAL FERMENTATIONS FOR FUEL ETHANOL
Pentose conversion by *Thermoanaerobacter ethanolicus*

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Lignocellulosic materials are promising substrates for ethanol production, for reasons of wide availability, low environmental impact, lack of competing food uses, favourable overall energy balance, and low cost. The two major obstacles to the use of lignocellulosics are the high cost of cellulose hydrolysis and the lack of a good pentose-fermenting organism.Thus,thermophilic bacteria seem particularly well suited for the fermentation of lignocellulosics because of their wide substrate spectra. They can be used to ferment enzymatically or chemically produced hydrolysates of cellulosic matericals; they can be used in a co-culture of a cellulolytic thermophile and a secondary thermophile that can ferment released monomers and oligomers.*Thermoanaerobacter ethanolicus*, which has a growth temperature optimum of 69°C, is an example of the secondary type of bacterium. We are studying its fermentation of xylose in order to assess its potential for industrial alcohol production.

Our previously published work described the continuous fermentation of low concentrations of xylose to ethanol by *T. ethanolicus* ATCC 31938. This work has now been extended by using higher xylose concentrations, with the goal of improving ethanol production paramenters. By altering the physicochemical environment, it was possible to increase the input xylose to 30 g l^{-1} (the concentration of hemicellulose hydrolysates from the dilute acid hydrolysis procedure) and still achieve a nearly complete xylose uptake at a dilution rate of 0.1 h^{-1}. While the product yield is found to be lower with the higher input xylose concentration, the fermentor ethanol concentration and volumetric productivity are found to be greater, with results that are similar to those of other thermophilic bacteria. While batch data from the studies of others show certain yeasts to be good pentose fermenters, *Thermoanaerobacter ethanolicus* exhibits a specific rate of ethanol production that is about twice that of the maximum rate recently quoted for pentose-utilizing yeasts.

Les matières lignocellulosiqes sont des substrats prometteurs pour ce qui est de la production de l'éthanol en raison de leur abondance, de leur faible impact sur l'environnement, de l'absence d'utilsation concurenti-elle, du bilan énergétique global favorable et de leur faible coût. Le coût élevé de l'hydrolyse de la cellulose et la fait qu'on ne dispose pas d'un organisme qui fermente bien le pentose sont les deux principaux obstacles qui s'opposent à l'utilsation des matières lignocellulosiques. Or, les bactéries thermophiles semblent particulièrement bien adaptées à la fermentation des matières lignocellulosiques puisqu'elles sont compatibles avec une grande variété de substrats. Elles peuvent servir à fermenter les hydrolysats de matières cellulosiques produits au moyen d'enzymes ou de produits chimiques; elles peuvent être utilisés dans une co-culture d'un thermophile cellulolytique et d'un thermophile secondaire capable de fermenter les monomères et les oligomères libérés. *Thermoanaerobacter ethanolicus*, qui présente une température de croissance optimale de 69°C, est un exemple de bactérie de type secondaire. Nous étudions en ce moment sa fermentation du xylose afin d'évaluer son potentiel pour ce qui est la production industrielle de l'alcool.

Dans des publications antèrieures, pour avons décrit la fermentation en continu de faibles concentrations de xylose en éthanol par *T. ethanolicus* ATCC 31938. On a maintenant étendu ces travaux en utilisant des concentrations de xylose plus élevées, dans le d'améliorer les paramètres de production d'éthanol. En modifiant l'environnement physico-chimique, il a été possible d'augmenter l'apport de xylose à 30 g/L (la concentration des hydrolysats d'hémicellulose produits par la méthode d'hydrolyse en présence d'acide dilué), tout en obtenant une absorption presque complète du xylose pour un taux de dilution de 0.1 h^{-1}. Même si rendement de produit est plus faible lorsque la concentration de xylose fourni est plus élevée, la concentration d'éthanol et la productivité volumétrique du fermenteur sont plus grandes, les résultats étant analogues à ceux que l'on obtient avec d'autres bactèries thermophiles. Bien que les données fournies par les études d'autres chercheurs montrent que certaines levures fermentent bien le pentose, *Thermoanaerobacter ethanolicus* présente un taux spécifique de production d'éthanol qui s'élève environ au double du taux maximal signalé récemment pour les levures qui utilisent le pentose.

INTRODUCTION

Lignocellulosic materials are promising substrates for fermentation alcohol production, for reasons of wide availability, low environmental impact, lack of competing food uses, a favourable overall energy balance, and low cost. However, analyses show that in order for the cost advantage of these substrates to be realized, the xylose constituents of the substrate (20-40% dry weight) must be fermented as well as the hexose constituents (Hinmann et al., 1988; Ladisch and Tsao) Depending on which pretreatment and hydrolysis procedure is applied to the substrate, the xylose will occur in one of the following hydrolyzates:

1) a xylose-rich prehydrolyzate derived from hemicellulose, separated from the cellulose;

2) a pretreated fraction containing hydrolyzed hemicellulose sugars and intact cellulose;

3) a hydrolyzate containing both pentoses and hexoses.

T. ethanolicus will likely not be applied in the last case. Its fermentation of hexoses, like that of all other thermophilic bacteria is far less efficient than that of *Saccharomyces cerevisiae* or *Zymomonas mobilis*. It does however, have potential application in the fermentation of a xylose rich fraction or as a xylose fermenting organism co-cultured with *Clostridium thermocellum*, a cellulolytic thermophile. In our earlier studies, very low concentrations of xylose, 4 g/l (27 mM), were employed in order to examine environmental parameters free from the effect of end-products. Continuous culture was adopted for such studies because it allowed manipulation of environmental parameters while keeping growth rate constant. Yields of 0.42 g/g were achieved in continuous culture from an input xylose concentration of 4 g/l, with growth rates of up to 0.3 per hour (Lacis and Lawford, 1988).

The purpose of the work reported here was to examine the ethanol production parameters of *T. ethanolicus* using xylose concentrations greater than 4 g/l. A number of environmental variables were manipulated, in order to bring about >95% utilization of xylose at higher concentrations. The organisms employed in these studies were strains previously isolated from xylose-limited chemostats. Their use improved the inter-trial reproducibility of chemostat experiments with low xylose concentrations. Furthermore, since these strains were isolated from chemostat samples of unusually high productivity, it was thought that the highest ethanol production parameters would be found using them.

MATERIALS AND METHODS

Microorganisms: Strain selection in chemostat

LL1 and LL2 are strains of *Thermoanaerobacter ethanolicus* derived from ATCC 31938 (high ethanol-producing mutant of ATCC 31550) and *T. ethanolicus* ATCC 31550 (wild-type), respectively. They were isolated by plating samples of chemostats displaying high volumetric productivity, and then recovering single colonies.

Media

The growth medium has been described previously (Lacis and Lawford, 1988). It contained phosphate buffer, magnesium chloride, a mineral supplement, a vitamin supplement, cysteine hydrochloride (a reducing agent), yeast extract (4 g/l), and various xylose concentrations (as specified).

Cultivation conditions

Details of the cultivation conditions are found elsewhere (Lacis and Lawford, 1988). Equipment included a New Brunswick model C30 fermentor equipped with a 750 ml glass jar with a working volume of approximately 350 ml. pH was maintained at 6.80 + 0.05 by using an Ingold combination electrode, 8 N KOH, and a New Brunswick pH controller. Temperature was maintained at 67.0 + 0.2 ^{o}C.

Sampling regimen

A minimum of two fermentor volumes were allowed to pass through the fermentor between samplings. This did not necessarily allow a true steady-state to be achieved for every sampling. However, since this allowed at least 86% of the fermentor volume to change, it is assumed that the 'pseudo-steady-state' samples obtained in the experiments nevertheless indicated the growth altering effects of the imposed changes.

Analyses

Xylose and fermentation products were analyzed by HPLC equipped with a Biorad HPX-87H column for organic acid analysis. Dry cell weights were determined by filtering culture broth through preweighed membrane filters (pore size, 0.45 µm), rinsing the cells with distilled waster, and drying under an infrared lamp.

Two- and three-carbon products, product yields, and units

The theoretical maximum of two- and three- carbon (C_2 + C_3) product (i.e. ethanol, acetate, lactate, 1,2-propanediol) yield from xylose is assumed to be 1.67 mol/mol (0.51 g/g).

RESULTS

Effect of environmental variables upon xylose uptake and ethanol yield:

A summary of the effect of particular environmental variables is shown in Table 1. The effects were determined by comparing two sequential 'pseudo-steady-state' samples where the indicated change in variable had been effected after the first sampling.

Effect of concentration of input xylose on fermentation products

Figure 1 shows the effect of input xylose concentration upon the fermentation products of the two selected strains, LL1 and LL2. Ethanol, lactate, acetate, and 1,2-propanediol,

in order of declining molar yield, were the 2- and 3-carbon products of fermentation.

The system was no longer xylose-limited at concentrations of about 20 g/l xylose (133 mM) and 5.5 g/l (120 mM) ethanol. Input media with 30 g/l xylose yielded even less products than media with 20 g/l, implying that substrate concentrations of about 10 g/l were inhibitory under the experimental conditions.

Product yield from xylose and yeast extract

Data from the samples shown in Figure 1 were combined for the analysis shown in Figure 2, where total $C_2 + C_3$ products are plotted against xylose consumed. (Data from input substrate concentrations of 20 g/l (107 mM) were not used, since it was sometimes a non-limiting amount). This allowed the estimation through linear regression of a product yield of 1.3 mol $C_2 + C_3$ products/mol xylose consumed. Surprisingly it also indicated that 10 mM products would be obtained in the absence of xylose. This result was confirmed by the production in test tube culture of 8 mM products from medium with 4 g/l yeast extract and no xylose. This implied that yeast extract, as well as xylose, was being converted to products. A calculation of possible contributions to products from amino acid and nucleotide components of yeast extract confirmed that this was possible.

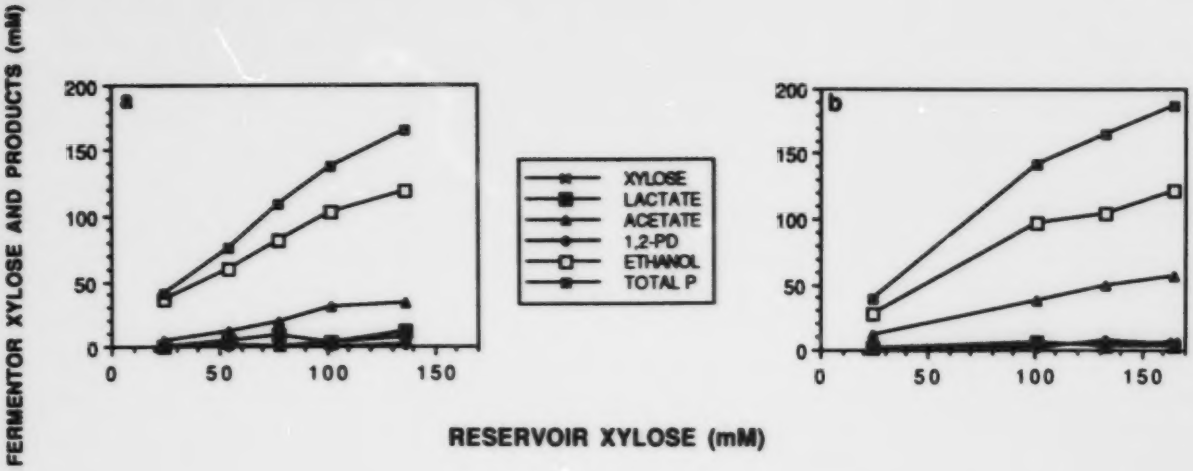
Optimized ethanol production parameters

Table 2 summarizes the maxima of ethanol production parameters obtained using higher input xylose concentrations. They are compared with corresponding parameters of other xylose fermenters.

Table 1: Effect of changes in environmental conditions upon ethanol yield and xylose utilization

Change in variable		Effect on: ethanol product fraction						Effect on: xylose utilization					
	TRIAL	a	b	c	d	e	f	a	b	c	d	e	f
$FeCl_3$ increase	(1X-2X)		+	+		·			+	·		·	
	(2X-3X)	·	+	·	-			·	+	·	·		
$ZnSO_4$ increase	(1X-2X)		·		·	·			+		·	·	
	(2X-3X)		·			·			·			+	
$CoCl_2$ increase	(1X-2X)		·			·			·			·	
Nicotinic acid increase	(1X-1.5X)		·			·			·			·	
	(1.5X-2X)						+						+
Phosphate buffer increase	(1X-4.4X)	·	·			·		·	-			·	
Dilution rate decrease (0.15 to 0.10 per hour)					·						+		
Agitation rate increase (200 to 300 or 400 rpm)		·	+			·		·	·			+	
Nitrogen flow increase (5 to 10 ml/min)		·				-		·				·	

Ethanol product fraction refers to the molar ratio of ethanol to the total of 2- and 3-carbon products (ethanol, lactate, acetate, and 1,2-propanediol). A change in xylose utilization was detected by measuring the change in the molar ratio of total 2- and 3-carbon fermentation products to xylose available. Statistical analysis was carried out in Materials and Methods. An increase or decrease in measurement is represented by a plus or minus symbol, respectively. Plain type indicates a significance of 0.05 or less; bold type indicates one of 0.01 or less. Dots indicate that the indicated change was carried out, but no significant effect ($p < 0.05$) was observed.



Figures 1a-b: Maximum ethanol concentrations, xylose and other fermentation products vs. input xylose concentrations. Included are samples with the maximum ethanol concentration observed at a particular input concentration of xylose. Figures a and b correspond to trials with LL1 and LL2 respectively. The maximum reservoir concentration indicated in Figure b is actually the calculated *effective* input concentration, as the sample was taken after the reservoir xylose concentration had been changed from 20 g/l (133 mM) to 30 g/l (200 mM).

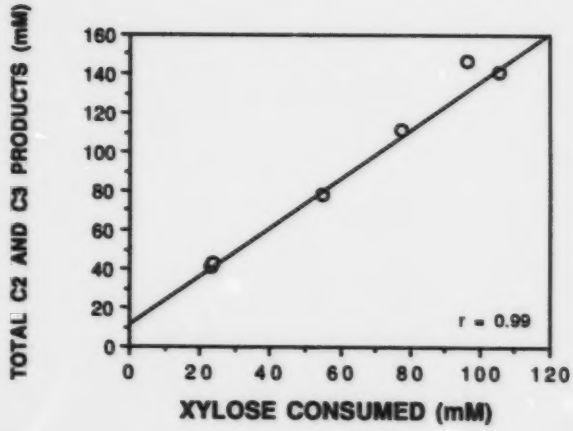


Figure 2: Regression of total $C_2 + C_3$ products against consumed xylose. Product data from samples shown in Figs. 1a-b were regressed against the corresonding concentration of consumed xylose. Samples with 20g/l input xylose were not included. The least-squares line extrapolates to a y-intercept of 1.0×10^1 mM, with a slope of 1.3. $r = 0.99$.

DISCUSSION

Xylose utilization

As mentioned, xylose utilization became limited when input xylose concentrations were about 20 g/l and ethanol concentrations were about 5.5 g/l (120 mM). Both hydrogen and ethanol are likely product inhibitors. Future experiments could test this hypothesis with the inclusion of these products in the input medium. If they did not exacerbate the effect of the limitation, a nutrient limitation would be suspected.

Ethanol yield

Ethanol yield is probably the most important parameter to consider in xylose fermentations because analyses of processes show cost to be highly sensitive to this parameter. The data of Fig 2 indicate that the maximum yield that one could expect from the conversion of xylose alone is 1.3 mol $C_2 + C_3$ product/mol xylose consumed, which is 78% of the theoretical maximum. This would thus be the limit for ethanol yield as well (i.e. 1.3 mol ethanol/mol xylose consumed or 0.40 g/g).

Analogous data from experiments with glucose as the substrate estimate a corrected $C_2 + C_3$ product yield that is 94% of the theoretical maximum (i.e. 1.9 mol $C_2 + C_3$ product/mol glucose consumed). There is no known reason for the efficiencies of $C_2 + C_3$ product recovery from glucose and xylose to differ. Greater activity of the pentose phosphate pathway and its decarboxylating reaction of 6-phosphogluconate dehydrogenase is implied by the lower C2 + C3 product recovery of xylose fermentations. It is feasible that the presence of xylose would induce greater activity of the pentose phosphate pathway, since some of its reactions pertain to the catabolism of xylose. If this were in fact the case, it would likely be possible to reduce the loss of carbon through the pentose phosphate pathway by isolating a mutant with a defect in 6-phosphogluconate dehydrogenase, since this reaction is not essential for pentose catabolism.

Not only did the yield of total $C_2 + C_3$ products from consumed xylose decreased as the substrate concentration was increased, but the proportion of products that was ethanol also declined. Thus, when the input xylose concentration was 16 g/l, a yield of only 0.74 mol ethanol/mol total $C_2 + C_3$ products was obtained. This decline could have resulted from the presence of greater product concentrations, or from the declining influence of yeast extract. It is possible that 0.74 represents a maximum imposed by metabolic constraints. The organism might require some conversion of xylose to acetate, in order to satisfy energetic requirements (since acetate production via acetate kinase yields more ATP than ethanol production).

Predictions of ethanol yields and concentrations from higher input xylose concentrations

The data obtained here can be used for estimating ethanol concentrations from yet higher substrate concentrations. Present results indicate that a yield of 0.97 mol ethanol/mol xylose (0.30 g/g) consumed should be used (based on 0.74 mol ethanol/mol total C2 and C3 products x 1.3 mol C2 and C3 products/mol xylose consumed). An optimistic adjustment would assume that 95% of the theoretical yield of C2 and C3 products could be obtained eventually from a mutant strain, thus giving a conversion factor of 1.2 mol/mol (0.36 g/g).

Comparisons with other xylose-fermenting microorganisms

Table 2 shows that the ethanol production parameters of *T. ethanolicus* are roughly comparable to those of other thermophilic bacteria and of pentose-fermenting yeast.

CONCLUSION

With present development of *Thermoanaerobacter ethanolicus*, a yield of 0.97 mol ethanol/mol xylose consumed (0.30 g/g) should be assumed for xylose fermentations with substrate concentrations greater than 20 g/l. Nevertheless, comparison of its parameters of ethanol production with those of the xylose-fermenting microorganisms of most interest indicate that further development of this organism and conditions for its fermentation are warranted.

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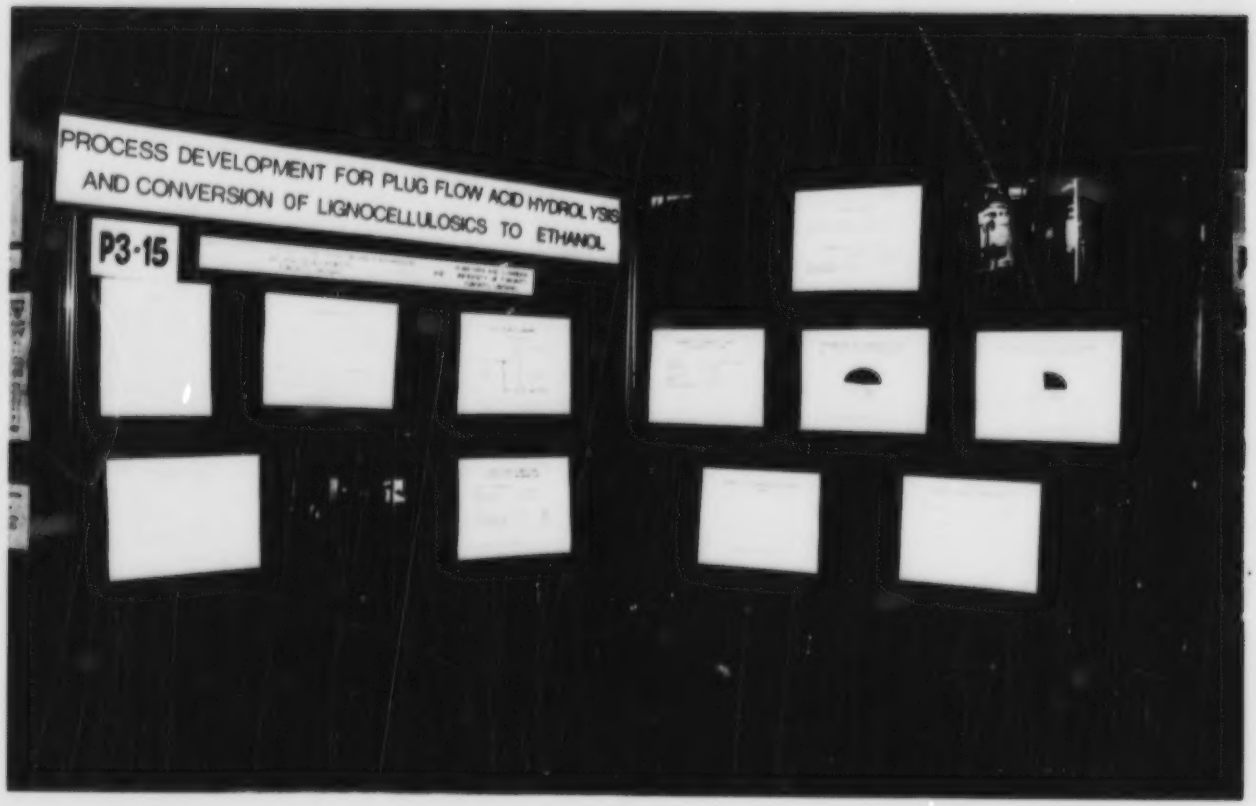
Table 2: Comparison of the *T. ethanolicus* continuous xylose fermentation with that of other microorganisms

	s	Xylose	E	$Y_{e/s}$	Q_e	q_e	Reference
T. ethanolicus							
LL1	15	97	4.7	0.32	0.47	0.56	this work
LL1	20	95	5.5	0.28	0.55	.	this work
C. thermosaccharolyticum							
HG-6	6	.	.	0.32	.	.	Liu et al. (1989)
HG-8	24	92	7.5	0.34	0.45	0.32	Mistry (1986)
HG-8	60	95	24	0.42	1.9	0.43	Kim (1982)
C. thermohydrosulfuricum							
39E	30	98	10	0.36	0.46	.	Sundquist et al. (1986)
C. shehatae	100	.	25	.	1.2	0.16	Alexander et al. (1988b)
	120	96	37	0.32	0.96	0.08	Alexander et al. (1988a)

Data were selected to present highest yields and concentrations of ethanol. Abbreviations represent the following: s, input xylose concentration (g/l); xylose utiliz'n, percentage of input xylose utilized; E, ethanol concentration (g/l); $Y_{e/s}$, yield of ethanol from xylose consumed (g/g); Q_e, volumetric ethanol productivity (g/l h); q_e, specific ethanol productivity (g/g h); ".", not reported.


PROCESS DEVELOPMENT FOR PLUG FLOW ACID HYDROLYSIS
AND CONVERSION OF LIGNOCELLULOSICS TO ETHANOL
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PROCESS DEVELOPMENT FOR PLUG FLOW ACID HYDROLYSIS AND CONVERSION OF LIGNOCELLULOSICS TO ETHANOL

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M. Holysh and P. Assarsson

Bio-Hol Developments

A process was developed at a pilot plant scale to convert wood (aspen and/or pine) to ethanol. Initially, the hemicellulose fraction of the wood was hydrolyzed (prehydrolysis) using SO_2 as the catalyst, in a Wenger single screw extruder, at a yield of up to 22.9% (aspen) and 24.7% (pine), based on the C_5/C_6 sugars produced as a function of the dry wood feed. The sugars produced were then recovered through a plate and frame filter press. The cellulose fraction of the prehydrolyzed wood was then hydrolyzed by dilute HCl acid catalysis in the SLR plug flow reactor. Yields up to 18.7% (pine) and 21.9% (aspen) based on the glucose produced as a function of the original wood feed were obtained. The glucose produced was then recovered through decanting and centrifuging. The prehydrolysate and hydrolysate streams were then fermented separately and together with the yeast strain Pichia stipitis. Yields (g ethanol/g sugar consumed) ranging between 0.44 and 0.49 were obtained from the fermentations. An economic evaluation was prepared on a 20,000,000 L/yr wood to ethanol plant, based on the data obtained from the pilot plant. It was determined that the plant would have an overall yield of 217 L/ODMT and require a capital investment of $18.5 million. The operating cost of the plant was estimated at 44.68 cents/L, based on a raw material cost of $46.20/ODMT.

On a mis au point au procédé à l'échelle pilote permettant de convertir du bois (tremble et/ou pin) en éthanol. On a d'abord hydrolysé la fraction hémicellulosique du bois (pré-hydrolyse), en présence de SO_2 comme catalyseur dans une extrudeuse Wenger à vis unique, à un rendement relatif (%) pouvant atteindre 22,9 (tremble) et 24,7 (pin) basé sur le rapport des sucres C_5/C_6 produits en fonction de la charge de bois sec. Les sucres ainsi obtenus étaient ensuite récupérés à l'aide d'un filtre-presse à plateaux et cadres. La fraction cellulosique du bois pré-hydrolysé était ensuite hydrolysée en présence de HCl dilué comme catalyseur, dans le réacteur SLR à écoulement en bloc. Nous avons obtenu des rendements pouvant atteindre 18,7% (pin) et 21,9% (tremble) basés sur le glucose produit en fonction de la charge initiale de bois. Le glucose produit était ensuite récuperé par décantation et centrifugation. Le pré-hydrolysat et l'hydrolysat étaient ensuite fermentés séparément et ensemble en présence de la levure Pichia stipitis. Nous avons ainsi obtenu des rendement (g d'éthanol/g de sucre consommé) variant de 0,44 à 0,49. Nous avons préparé une évaluation économique d'une usine d'éthanol d'une capacité de 20 000 000 L an, à partir des données obtenues à l'échelle pilote. L'usine aurait un rendement global de 217 L/TMSÉ* et nécessiterait un investissement de 18,5 millions de dollars. Les frais d'exploitation ont été évalués a 44,68 cents/litre en supposant un coût de 46,20 $/TSMÉ* pour les matières premières.

SLR - St. Lawrence Reactor
ODMT - Oven Dried Metric Tonnes
TSME - Tonnes Metriques de Bois Seche

INTRODUCTION

The work performed for this project was a continuation of work previously undertaken by St. Lawrence Reactors and the University of Toronto under a funding agreement with the Ontario Ministry of Energy entitled, "Research into Cost Effective Fuel Ethanol Process from Indigenous Raw Material Sources". In that project a process, incorporating the SLR plug flow reactor for both hemicellulose and cellulose hydrolysis, for converting various types of cellulosic materials to ethanol was investigated. It was determined that although the plug flow reactor was able to hydrolyze the hemicellulose fraction of wood at a high yield (approximately 90%), the reactor was only capable of processing wood slurries of 5% DS (Dried Solids), which was deemed unfeasible for commercial process.

The objective of this project was to investigate a wood to ethanol process incorporating a Wenger single screw extruder for hemicellulose hydrolysis (prehydrolysis) and the SLR plug flow reactor for cellulose hydrolysis. A Wenger single screw extruder was chosen as a

substitute for the SLR plug flow reactor for prehydrolysis, due to its ability to handle wood slurries of a high dry solids content (50%)

The fermentation work covered in this project was performed by Professor Morris Wayman of the University of Toronto. The fermentations performed primarily investigated the suitability of the yeast strain Pichia stipitis to ferment both the C_5 and C_6 sugars produced.

Through experimentation an overall process scheme was developed and optimized and the economics for a semi-commercial plant were analyzed.

EQUIPMENT

Wenger Single Screw Extruder

The Wenger extruder was used for prehydrolysis (hemicellulose hydrolysis). This extruder had been used previously for H_2SO_4 catalyzed hydrolysis of both aspen and pine. In previous work the extruder was found capable of processing wood sawdust of a high dry solids content (approximately 50%) and operating at pressures up to 1500 psig and temperatures up to 230°C.

The system used consisted of: a paddle mixer in which the moisture of the wood feed was adjusted; a vibrator and cyclone vacuum system to transfer the feed to the live bin of the extruder; and a screw feeder to the extruder including an acid injection port. The temperature and pressure of the extruder were monitored by a strip chart recorder during each run.

SLR Plug Flow Reactor

The SLR reactor was used for the acid catalyzed hydrolysis of the cellulose fraction of the wood. The reactor system consisted of two sections: two low pressure shells which were used to heat up the feed material to approximately 167°C; and one high pressure shell in which temperatures of up to 230°C were attained. The shells each contained three sets of 1 in tubing in which the material travelled. The tubing was constructed of a special ferritic steel and was indirectly heated with steam. A Robbins and Myers 9P4 progressive cavity Moyno pump was used to feed the reactor. A 0.15 in orifice was used to maintain the back pressure within the reactor.

Separation Equipment

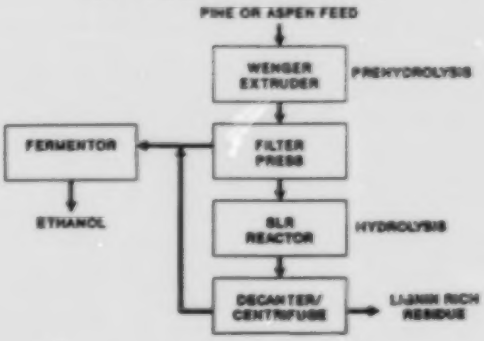
A Perrin plate and frame filter was used for washing the extruded prehydrolyzed wood material to recover the sugars produced from prehydrolysis.

A Westfalia CA 220 decanter/clarifier and a Westfalia SB 14 de-sludger/clarifier were both used for the solid/liquid separation of the plug flow hydrolyzed material.

EXPERIMENTAL PROCEDURE

The pilot plant flow sheet is shown in Figure No. 1. Wood slurries of both pine and aspen ranging in dry solids content of between 55 and 60%, and 55 and 70% respectively, were prepared in the paddle mixer. The wood slurry was fed into the extruder at an acid loading ranging from 1.0 to 3.0% SO_2/dry wood feed. During the course of each experiment the temperatures and pressures along the barrel of the extruder were monitored. The extruder was operated at temperatures and pressures of up to 180°C and 1200 psig respectively at the outlet. The product was collected at timed intervals which permitted the mass flow rate of the product to be determined.

FIGURE NO 1
PILOT PLANT FLOWSHEET



The extruded wood product was slurried up and passed into the filter press. The cake obtained was then processed through the plug flow reactor. The feed material to the reactor had a dry solids content of approximately 17%. The orifice and coil length utilized throughout the experimentation were 0.15 in and 120 ft respectively. The acid strength (HCl/(HCl + Water)) was maintained at 0.3%, which corresponded to a pH of 1.5 and an acid/wood ratio of 1.5%. The residence time in the reactor was varied between 1.3 and 2.5 minutes and the temperature ranged from 215°C to 226°C. The temperature of the reactor was varied by adjusting the pressure of the boiler and the residence time in the reactor was controlled through the speed of the pump. The product obtained from the reactor was collected at timed intervals.

The hydrolyzed material was diluted with water and passed through the clarifier/decanter and/or desludger/clarifier to recover the sugar solution produced. The sugar solution was then concentrated for fermentation.

The prehydrolysate, hydrolysate and combined prehydrolysate and hydrolysate streams were fermented at the University of Toronto using shake flasks and a 4 L fermentor and at Bio-Hol in a 28 L fermentor. The fermentations were performed utilizing Pichia stipitis.

RESULTS AND DISCUSSION

Prehydrolysis

The prehydrolysis experiments with the extruder

utilized SO_2 as the catalyst. Initially the extruder was operated with a low flow rate (4.0 lbs/min). It was observed during these runs that the outlet flow was surging and that the product was inconsistent. The extruder was then shipped back to Wenger Manufcturing in order that the appropriate modification could be made to allow for a higher flow rate and smoother operation. The modifications made to the extruder allowed for the feed rate to be increased by over 200% for both pine and aspen. A smoother product flow rate and a consistent product were also obtained.

The results from the prehydrolysis runs performed on the modified extruder are shown in Table No. 1. The maximum yields (% total sugars/ dry wood feed) obtained were 24.7% (pine) and 22.9% (aspen). The percentage of wood solubilized during prehydrolysis ranged between 32&35% (pine) and 32&39% (aspen). In all the runs performed 100% of the hemicellulose fraction of the wood was hydrolyzed, while the percentage of the cellulose fraction of the wood hydrolyzed during pre-hydrolysis ranged between 20&40% of the pine and 8&34% for the aspen.

TABLE NO 1

PREHYDROLYSIS : WENGER EXTRUDER

OPERATING CONDITIONS

FEED	6-9 LBS/MIN
DRY SOLIDS IN FEED	50-70 %
TEMPERATURE	165-175 DEG C
SO2/DRY SOLIDS	1.5-3.0 %

RESULTS

	ASPEN	PINE
XYLOSE-MANNOSE/WOOD	14.5 - 18.8 %	15.8 - 17.8 %
TOTAL SUGARS/WOOD	18.9 - 22.9 %	22.3 - 24.7 %
WOOD SOLUBILIZED	32.0 - 39.0 %	32.0 - 35.0 %
CELLULOSE CONVERSION*	8.0 - 34.0 %	20.0 - 40.0 %

* 100% HEMICELLULOSE CONVERSION WAS OBTAINED

Hydrolysis of Prehydrolyzed Material

Cellulose hydrolysis of the prehydrolyzed material was performed in the SLR plug flow reactor. HCl was used as the acid catalyst for the reaction. The results obtained from the hydrolysis runs are shown in Table No. 2. The dry solids content of the feed material ranged between 14 and 18%. The residence time in the reactor ranged between 1.4 and 2.3 minutes, which corresponds to a feed rate ranging between 14 and 23 lbs/min. The reaction temperature in the reactor was maintained between 216°C and 226°C.

The maximum yield (% glucose/original wood) for pine, 18.7%, was obtained at a temperature of 220°C, a residence time of 2.4 minutes and a % acid/dry feed of 1.5. The maximum yield for aspen, 21.9% was obtained at a temperature of 226°C, a residence time of 1.4 minutes and a % acid/dry feed of 1.6. The cellulose conversion in the plug flow reactor ((cellulose feed-cellulose product) / cellulose feed) ranged between 50 and 80%.

TABLE NO 2

CELLULOSE HYDROLYSIS : SLR REACTOR

OPERATING CONDITIONS

FEED	14 - 23 LBS/MIN
DRY SOLIDS IN FEED	14 - 18%
TEMPERATURE	216 - 226 DEG C
HCl/DRY FEED	1.5 - 1.8 %

RESULTS

	ASPEN	PINE
GLUCOSE/ORIGINAL WOOD	15.3 - 21.9 %	16.7 - 18.7 %
GLUCOSE/CELLULOSE *	33.8 - 48.3 %	45.8 - 65.0 %
CELLULOSE CONVERSION*	52.9 - 66.7 %	49.6 - 78.2 %

* BASED ON CELLULOSE IN FEED TO SLR REACTOR

Washing of the Prehydrolyzed and Hydrolyzed Material

The washing of the prehydrolyzed material was performed with a Perrin plate and frame filter press, while both a decanter and centrifuge were used to wash the hydrolyzed material. Mass balances were performed around the apparatus used to determine the washing efficiencies.

The prehydrolyzed material was diluted to 20% DS (2 parts water: 1 part prehydrolyzed material) for each wash. It was determined that a washing efficiency of approximately 95% could be achieved in a two stage washing system. The hydrolyzed material was diluted to 10% DS (1 part water: 1 part hydrolyzed material). It was determined that a 95% washing efficiency could also be achieved in a two stage washing system with the hydrolyzed material.

Fermentations

The fermentation work for this project was performed under subcontract by Professor Morris Wayman of the University of Toronto. The prehydrolysate and hydrolysate streams obtained were fermented separately and together in either a 4 litre or 28 litre fermentor, with the yeast strain *Pichia stipitis*. The prehydrolysate stream had to be steam stripped, to reduce the acetic acid concentration to below 0.5g/L before being fermented.

The results obtained from the various fermentations runs performed on both the pre-hydrolysate streams and the combined prehydrolysate and hydrolysate streams are shown in Table No. 3. In the fermentations performed on the pre-hydrolysate streams the initial sugar concentration was between 53 and 60 g/L. The yields obtained (Yp/s: g ethanol/g sugar consumed) ranged between 0.44 and 0.49. The % sugar consumed in the fermentations of the prehydrolysate was 90%. In the fermentations of the combined prehydrolysate and hydrolysate streams the initial sugar concentration was between 102 and 116 g/L. The yields (Yp/s) obtained from the fermentation of the combined streams ranged between 0.43 and 0.45 while the % sugar consumed averaged 95%.

TABLE NO 3

FERMENTATION RESULTS

	PREHYDROLYSATE	PREHYDROLYSATE /HYDROLYSATE
INITIAL SUGAR CONC	53 - 60 g/L	102 - 116 g/L
g ETOH/g SUGAR CONS	0.44 - 0.49	0.43 - 0.45
SUGAR CONSUMED	90 %	95 %
FINAL ETHANOL CONC	23.5 - 24.0 g/L	45.3 - 46.5 g/L

ECONOMIC EVALUATION

An economic evaluation was performed on a wood to ethanol plant based on the data obtained through experimentation. The proposed plant would be integrated with a pulp and paper mill based in Northern Ontario. Based on data obtained from industrial sources it is assumed that the pulp mill would generate enough waste pine wood to support a 20,000,000 L/yr ethanol plant. For this evaluation the feedstock cost was estimated at $46.20/ODMT (fuel value equivalent of the waste wood) and the selling price for ethanol was estimated at 40 cents/L.

A summary of the details of the plant is shown in Table No. 4. The overall yield of the plant was estimated at 217 L/yr. The fixed capital investment for the plant was estimated at $18.5 million. The chart shown in Figure No.2 outlines the capital costs associated with the individual components of the plant. This figure demonstrates that the prehydrolysis section of the wood represents approximately 25% of the total fixed capital cost.

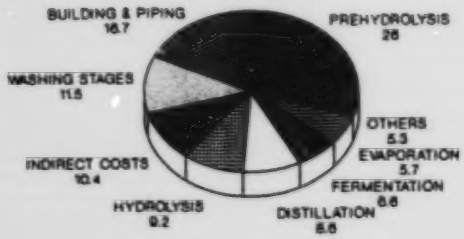
TABLE NO 4

WOOD TO ETHANOL PLANT - 20,000,000 L/YR

FEEDSTOCK	PINE WASTE FROM PULP MILL
FEEDSTOCK COST	$46.20/ODMT
OVERALL YIELD	217 L/ODMT
OPERATING COST	44.68 CENTS/L
CAPITAL INVESTMENT	$18.5 MILLION

FIGURE NO 2

PERCENTAGE OF FIXED CAPITAL INVESTMENT 20,000,000 L/YR ETHANOL PLANT

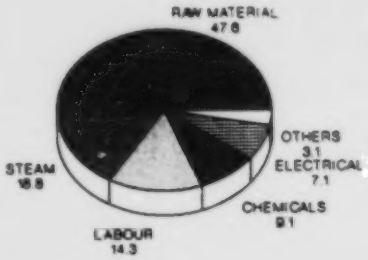


TOTAL CAPITAL INVESTMENT $18.5 MILLION

The total operating cost of the plant was estimated at 44.68 cents/L. Figure No. 3 outlines the individual components of the total operating cost. The chart shown in Figure No. 3 demonstrates that the raw material cost represents almost 50% of the total operating cost.

FIGURE NO 3

PERCENTAGE OF OPERATING COSTS 20,000,000 - L/YR ETHANOL PLANT

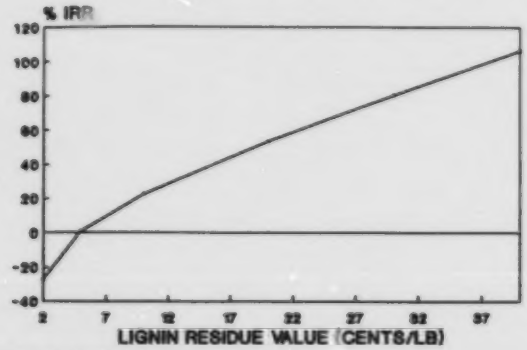


TOTAL OPERATING COST 44.68 CENTS/L

Sensitivity analyses were performed to determine which variable had the greatest effect on the internal rate of return (IRR) of the proposed plant. Through this analysis it was determined that the value of the lignin rich residue produced from the plug flow reactor had the greatest effect on the IRR. The effect of the lignin rich residue on the IRR is shown in Figure No. 4, based on a selling price of ethanol of 40 cents/L. This figure demonstrates that a value of 10 cents/lb for the residue would result in an IRR of over 20%. The residue produced from the plug flow reactor contains over 60% lignin. The value of this material has not yet been evaluated, however work is on going at Bio-Hol to determine the value of the residue and to purify the lignin content.

FIGURE NO 4

EFFECT OF LIGNIN RESIDUE VALUE ON IRR



* SELLING PRICE OF ETHANOL = 40 CENTS/L

CONCLUSION

This project demonstrated that the Wenger extruder and SLR plug flow reactor could be incorporated together into a wood to ethanol process. The Wenger extruder was found capable of processing wood slurry feeds of up to 68% DS and producing C5/C6 sugars at a yield of up to 24.7% (pine) and 22.9% (aspen) based on the dry wood feed. The SLR reactor was found capable of processing the prehydrolyzed material at up to 17% DS and obtaining sugar (glucose) yields of up to 18.7% (pine) and 21.9% (aspen), based on the original wood. The yeast strain Pichia stipitis was found to be capable of fermenting both the prehydrolysate and hydrolysate streams and a combination of the two streams. The yields (Yp/s: g ethanol/g sugar consumed) obtained from the fermentations averaged 0.45.

An economic evaluation based on the data obtained through experimentation demonstrated that a 20,000,000 L/yr wood to ethanol plant, integrated with a pulp and paper mill in Northern Ontario, would require a capital investment of $18.5 million and would have an operating cost of 44.68 cents/L. The overall ethanol yield from the plant was estimated at 217 L/ODMT.

A sensitivity analysis demonstrated that the value of the lignin rich residue produced from the plug flow reactor had the greatest effect on the IRR of the proposed plant. The analysis demonstrated that an IRR of over 20% could be achieved if the lignin rich residue could be sold for 10 cents/lb. Work is presently being performed at Bio-Hol to determine the value of the lignin residue and to determine methods to up-grade its value.

ACKNOWLEDGEMENT

The authors would like to thank both the Ontario Ministry of Energy and Energy, Mines and Resources Canada, for funding this work.

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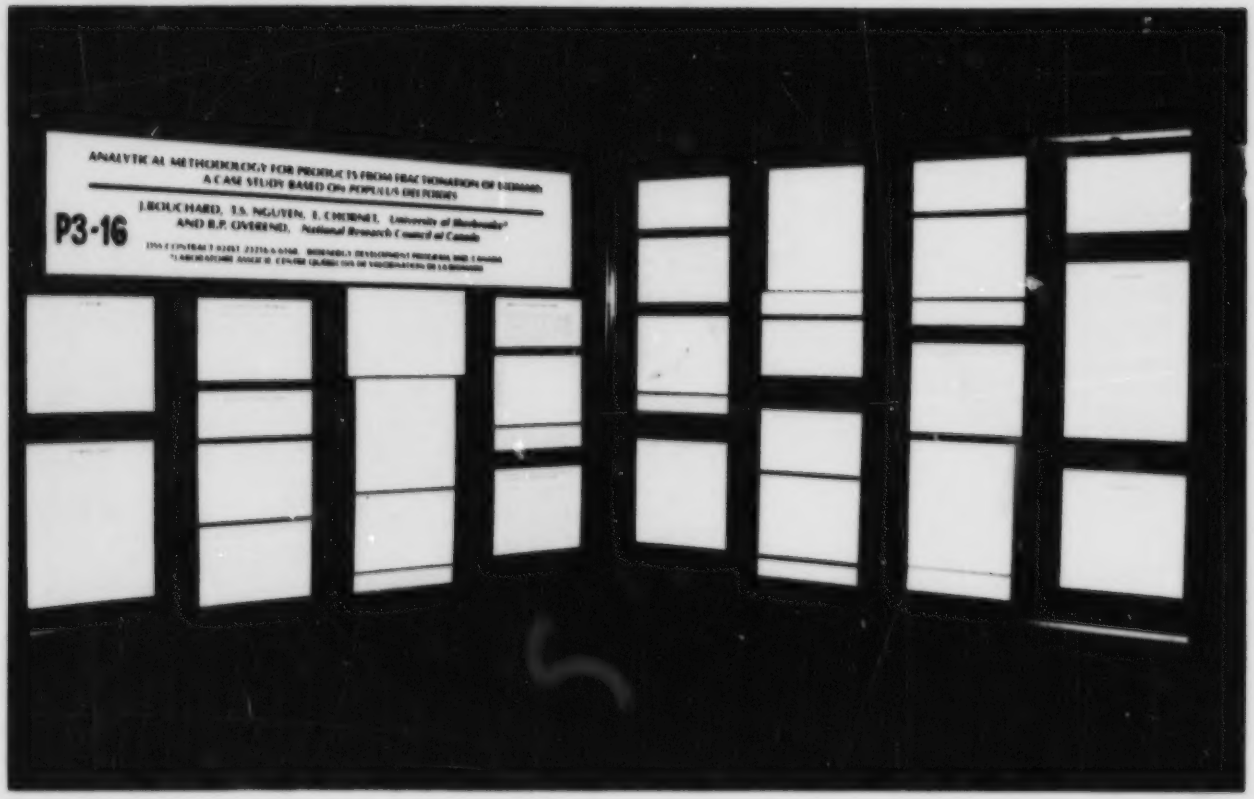
ANALYTICAL METHODOLOGY FOR PRODUCTS FROM FRACTIONATION OF LIGNINS
A CASE STUDY BASED ON POPULUS DELTOIDES
P3-16
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ANALYTICAL METHODOLOGY FOR PRODUCTS FROM FRACTIONATION OF BIOMASS: A CASE STUDY BASED ON POPULUS DELTOIDES*

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Populus Deltoides was pretreated using a steam/aqueous thermo-mechanical process in which shear forces are applied by rapid passage of medium consistency slurries through homogenizing valves. In this paper the characterization of the residual and soluble wood fractions by standard, thermal (TG, DSC) and spectroscopic (DRIFT) methods is presented. The results are discussed in terms of the effect of the severity of the treatment on the macrostructure of the different wood polymers. An evaluation of standard (ASTM) methods for quantification of these polymers in treated wood is presented.

Populus Deltoides a été traité par un procédé thermo-mécanique en milieu aqueux. Des forces de cisaillement sont générées par passage rapide d'une suspension de consistance moyenne à travers des valves d'homogénisation. La présente communication fait état de la caractérisation des fractions solubles et résiduelles par des méthodes standards, thermiques (TG, DSC) et spectroscopiques (FTIR). Les résultats sont évalués dans le cadre de l'effet de la sévérité du traitement sur la structure des polymères du bois. Nous avons procédé à une évaluation des méthodes standards (ASTM) pour la quantification de ces polymères dans des échantillons traités et des procédures correctives sont proposées.

* DSS contract #24ST.23216-6-6168, Bioenergy Development Program, EMR, Canada

INTRODUCTION

Steam/aqueous treatments can be considered as thermomechanochemical processes since heat, shear forces and hydrolysis are combined to destructure the lignocellulosic matrices in order to meet different objectives: production of low cost sugars; increase the accessibility of the cellulosic carbohydrate to cellulases; use of low cost residual lignocellulosics as feed for ruminants. A more recent objective of steam and aqueous pretreatments has been the fractionation of lignocellulosics to obtain each of the polymeric components in maximum yield and purity. We felt that a study of how the constitutive polymeric fractions change as a function of the treatment severity for a generic steam/aqueous process was a worthwhile goal to pursue in order to better understand the principles of fractionation as well as the possible uses of the polymers themselves after treatment.

The generic steam/aqueous treatment used in our study has been described previously by Koeberle et al.[1]. It is based on a methodology in which an aqueous suspension of finely divided lignocellulosics at medium solids consistency is rapidly heated by steam addition and passed through homogenizing valves[2]. By treating Populus Deltoides (a prototypical hardwood) in the steam/aqueous fractionation unit at different severities, our main objective was to obtain a detailed view of the changes of the constitutive polymers in the treated materials by characterization of the soluble and solid residual fractions as a function of the severity of the treatment. A second objective was to critically evaluate the standard methods used for quantification of constitutive polymers as a function of the severity of the treatment.

MATERIALS AND METHODS

The UdeS fractionation process and the severity scale (R_o)

The wood used is the NRCC reference material, Populus Deltoides, milled and swelled in water at a 10% w/w concentration. For each experimental point, 1.5 liters are pumped through the reactor system for a period of two minutes while temperatures were varied from 180°C to 235°C. Time (t) and temperature (T) have been combined into a single factor called Reaction Ordinate (R_o) which represents the severity of the treatment[3] as expressed in Equation (1). In the present study, the log function of R_o is used.

$$R_o = t * \exp\left[\frac{T - 100}{14.75}\right] \qquad (1)$$

Analytical methodology

Four different fractions were obtained from fractionation of Populus Deltoides: residues (R); soluble fractions (S); ethyl acetate-extracted aqueous fractions (S_{AP}) and the organic (ethyl acetate) phases (S_{OP}). Each fraction was analyzed following the analytical procedure described previously[4].

RESULTS AND DISCUSSIONS

Experimental conditions used in the steam/-aqueous fractionation process for Populus Deltoides and the conversions obtained in g of dissolved solids/100 g of initial wood are shown in Table 1. The sample PD-1.3 represents the untreated wood which has been extracted with hot water for 7 hours. For severities (log R_0) ranging from 2.65 to 4.3, the solubilization ranges from 5% to 32% of the wood.

1- Quantification of hemicellulose, cellulose and lignin in solid residues by standard and corrected methods.

The distribution of water-soluble products and the residual polymeric families of the residues are shown in Table 2 as a function of severity. The cellulose and hemicellulose data obtained by the ASTM procedures are identified as standard (STD). The low yields of hemicellulose solubilization coupled with the cellulose solubilization indicated to us that something was wrong with the analytical procedure. We then decided to use a new approach based on the hypothesis that steam/aqueous treatment of wood can induce structural reorganisation of the cellulose network via hydrogen bonding modifications. Consequently, a part of the cellulose becomes soluble in sodium hydroxide solution used for α-cellulose quantification. In this case, the solubilized cellulose will be "counted" as hemicellulose and give erroneous results.

The correction procedure implies a reconstitution of the hemicellulose fraction from the carbohydrate analysis:

- quantification of xylose and arabinose from furfural produced by extensive hydrolysis (pentosan method)
- correction of the monosaccharides concentration obtained by GLC quantification of their silyl derivatives after hydrolysis of the wood residues using the correction factor calculated from the pentosan analysis
- distribution of the galactose, mannose and glucose concentration as a function of their cellulosic or hemicellulosic origins (distribution factors were obtained from monosaccharide analysis of soluble hemicellulose)
- calculation of the cellulose and hemicellulose concentration in treated residues using the above data.

These new results shown in the Table 2 (CORR) are represented in Figure 1 as cummulative composition of treated wood. Two conclusions may be drawn:

- The steam/aqueous fractionation process leads to an extensive solubilization of the hemicellulose (over 90%) as well as a small part of the lignin which will be quantified in the analysis of the filtrates.
- all the cellulose remains in the residues but the steam/aqueous process induces structural modifications on the cellulose which leads to solubilization of a fraction in sodium hydroxide solution. This alone is responsible for the quantification error made when using the standard method for α-cellulose determination.

2- Cellulase activity on wood and treated residues

The cellulases saccharification yields (in g/100 g of glucose potential) have been determined for periods of 24 hours incubation and the results are shown in Figure 2 as a function of the severity. Saccharification yield for native wood is below 20% of the glucose potential indicating that there is a structural barrier constraining the saccharification. The destructuration is maximized by the steam/aqueous fractionation process at a severity index of 3.2 where the yield of saccharification reaches 85%. Increasing the severity over 3.2 decreases the saccharification yield slightly.

3- Extraction of the soluble fractions by ethyl acetate and determination of the polyphenolics distribution

Each soluble fraction has been extracted by ethyl acetate. The objective was to separate the polyphenolic from the hemicellulosic fraction. The results are presented in Table 3 where the results are given in g/100 g of dissolved solids. The organic phases of the soluble fractions (S_{OP}) increase from 4% to 11% as a function of the severity indicating an increase in the solubilization of hydrophobic materials with the severity of the treatment. The efficiency of the ethyl acetate extraction can be estimated by determining the distribution of the polyphenolic products. The concentration of polyphenolics in water-soluble fractions varies between 7-11% of the total dissolved solids as shown in Table 4. More than the half of the polyphenolics are extracted by ethyl acetate in all samples. The non-extracted polyphenolics could be too hydrophylic or linked to carbohydrates. The concentration of polyphenolics in the aqueous phase is always below 5% of the dissolved solids. We can conclude that the ethyl acetate extraction of the soluble fractions is a useful pretreatment prior to more specific analyses.

4- Carbohydrates, O-acetyl and methoxyl groups recovery

No carbohydrate has been detected by HPLC monosaccharides analysis of the soluble fractions indicating that the hemicelluloses are solubilized in their polymeric form or charged oligosaccharides which are retain by the guard column of our HPLC system. The pentosan determinations were done on residual solids and the aqueous phase of the soluble fractions (S_{AP}) and the results are shown in the Figure 3-A. They indicate a

maximum of solubilization of 65% at the highest severity and a maximum of pentosan recovery which decreases from 100% to 70% as a function of the severity. The fact that 30% of the pentosan were lost during the treatment while no monosaccharide was detected in the soluble fraction remain unexplained.

In order to determine the role played by acetic acid in the autohydrolysis process, we found simpler, instead of determine the acetic acid amounts, to quantify the O-acetyl groups present in the soluble and residual fractions as shown in Figure 3-B. From an index of severity of 1.3 to 3.2, the O-acetyl content increases from 3.34% to 3.65% indicating that the method used cannot liberated 100% of the acetyl group in native wood. Some of them remain inaccessible to the acid attack if no destructuring treatment is done. We have decided to used the value of 3.65 g/100 g of wood as the total O-acetyl content of Populus Deltoides. From Figure 2-B, it becomes evident that the acetic acid is not involved in the autohydrolysis process below a severity of 3.9 because no deacetylation was observed. At a severity of 3.9, 11% of the acetyl group has been liberated while this proportion increases to 23% at a log R_0 of 4.3.

The methoxyl groups have been quantified in residual and soluble fractions. The results are shown in Figure 3-C. As it was the case for the quantification of the O-acetyl group, we observe an increase of the overall methoxyl content which reaches a maximum at log R_0 of 3.2. If we assume that some methoxyl group remain inaccessible to the acid attack until a destructuring treatment is done, the maximum value of 5.8 g of $-OCH_3$/100 g of wood should be used in order to determine the importance of demethoxylation reaction occuring during the process. The results of Figure 2-C lead to the conclusion that demethoxylation begins at a severity of log R_0 = 3.6 but even at the highest severity, over 87% of the methoxyl group remain fixed on residual or soluble lignin.

5- FTIR analysis of the soluble fractions (S, SAP and SOP)

The Figure 4 shows the evolution of the infrared spectra of the soluble fractions as a function of the severity. The hemicellulosic character and, at a lesser proportion, the lignin character of the soluble fractions increase with the severity. The lowest severity sample (log R_0 = 2.6) exhibits the same bands as the other samples but in a completely different proportion indicating that the species firstly solubilized have a different relative chemical composition than the others. This spectra indicates an important aromatic composition probably not related to lignin but to wood water extractives which represent 36% of this fraction.

The Figure 5 shows, for the sample treated at a severity of 3.9, the FTIR spectra of the whole soluble fraction, the aqueous phase (S_{AP}) and the organic phase (S_{OP}) obtained after the ethyl acetate extraction. From these spectra, it can be seen that the area mostly affected by the extraction is the 1700-1500 cm^{-1} which is closely related to lignin absorption bands. The predominant bands of the organic phase (S_{OP})spectra are those related to lignin. Two new bands have appeared at 854 and 830 cm^{-1} and are related to tri- and tetra-substituted benzene ring in lignin. Bands related to hemicellulose are still present indicating that some hemicelluloses have also been extracted.

6- Differential Scanning Calorimetry (DSC) of residues and soluble fractions

An indication of the influence of the treatment severity on thermal behaviour of polymers is given in Figure 6-A showing the thermogram obtained by DSC under air atmosphere of the residues. The first exotherm at 325°C is related to cellulose thermal degradation and seems unaffected by the steam/aqueous treatment. The small exothermic deviation of the baseline between 250 and 305°C, attributed to the hemicellulose, decreases as a function of the severity. The second exotherm in the 400-500°C area is mainly related to thermal degradation of the lignin. The maximum temperature and the relative intensity of the lignin exotherm vary as a function of the severity of the treatment. The temperature of the maxima decrease from 455°C to 435°C at a severity of 3.2. This is followed by an increase of the temperature to 495°C for the highest severity. The variation in the lignin exotherm suggests a chemical and/or physycal transformation of the polymer during the steam/aqueous treatment.

The Figures 6-B and 6-C show respectively the thermograms of the severity. Two high temperature exotherms can be identified in the Figure 6-B: 420-440°C and 450-465°C peaks. The first one disappears completely after the extraction for the low severities samples and partially for the higher severity samples. The second exotherm remains unaffected by the extraction. This leads to the conclusion that the two polyphenolic fractions, the one which is extracted by ethyl acetate and the one which is not, have two different thermal behavior and they compose two distinct lignin-derived polyphenolic families soluble in water.

CONCLUSION

The characterization of Populus Deltoides residual and soluble fractions obtained by steam/aqueous process as a function of the severity has led to the following conclusions:

- The steam/aqueous process leads to the solubilization of nearly one third of the wood at the highest severity used (log R_0 = 4.3). At this severity, over 90% of the hemicellulosic fraction is solubilized along with the water extractibles and a small part of the lignin (below 15% of the initial lignin). The standard (ASTM & TAPPI) α-cellulose test

has been demonstrated to fail as the severity of the pretreatment increases. By means of hydrolysis and quantification of the cellulose from the glucose content, we have confirmed that part of the cellulose fraction is soluble in solutions of sodium hydroxide. The change in method also requires that we "reconstitute" the hemicellulosic fraction from the monomers analysis.

- Ethyl acetate extraction of the soluble fraction is recommended prior analytical study and is efficient to removed lignin-derived hydrophobic material.
- Standard method for acetyl and methoxyl groups quantification underestimate their respective concentration in native wood. Deacetylation and demethoxylation occur only at high severity and their respective yields never exceed 25% and 13%.
- The fractionation process induces modifications in the thermal behaviour of the residual lignin and also conducts to the solubilization of distinct polyphenolic families as shown by the DSC analysis.
- The fractionation objectives are reached by the steam/aqueous treatment process: thus, the solubilization of the hemicellulose, the relative decrease of lignin solubilization at increasing severity and the important increase of cellulose accessibility to enzymatic hydrolysis are all characteristic features of the process.

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TABLE 1: Conversion of *Populus Deltoides* obtained by the UdeS-F steam/aqueous fractionation process.

SAMPLE	TEMPERATURE (°C)	log R_o	CONVERSION*
PD-1.3	55.0	1.29	1.8
PD-2.6	179.8	2.65	5.0
PD-3.2	201.0	3.27	11.2
PD-3.6	210.2	3.55	17.4
PD-3.9	220.4	3.85	26.1
PD-4.3	235.0	4.28	31.9

* *Conversion is in g of dissolved solids/100g of dry wood*

TABLE 2: Distribution of soluble products and residual polymeric families in *Populus Deltoides* treated by the UdeS-F steam/aqueous fractionation process (in g/100g of initial wood sample).

SAMPLE	FILTRATE	RESIDUE				
		CELLULOSE		HEMICELL.		LIGNIN
		STAND.	CORR.	STAND.	CORR.	
PD-1.3	1.8	42.0	42.5	32.1	31.6	24.2
PD-2.6	5.0	40.1	40.3	31.5	29.5	23.8
PD-3.2	11.2	41.6	40.3	23.6	24.2	22.2
PD-3.6	17.4	42.5	41.1	15.7	16.2	21.6
PD-3.9	26.1	40.6	40.1	11.5	7.8	20.5
PD-4.3	31.9	33.8	39.8	13.5	1.7	20.7

FIGURE 1

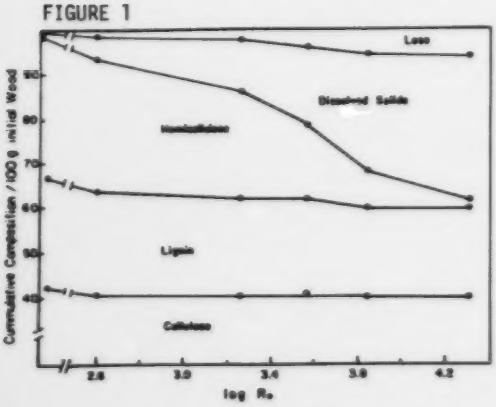


FIGURE 2

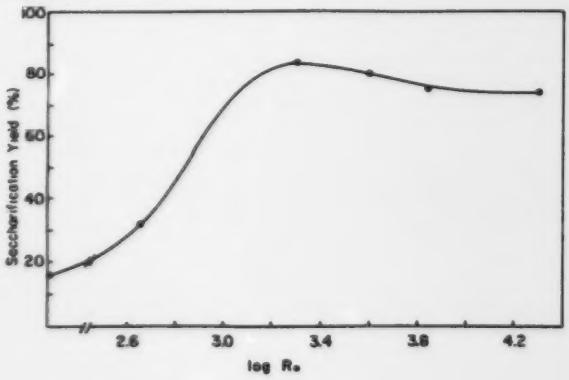


TABLE 3: Fractionation of soluble fractions by ethyl acetate extraction (in g/100g of dissolved solids).

SAMPLE	AQUEOUS FRACTION	ETHYL ACETATE FRACTION (S_{EF})		
	(S_{AF})	NON-VOLATILE	VOLATILE	TOTAL
S-2.6	95.8	4.2	---	4.2
S-3.2	93.7	6.2	0.1	6.3
S-3.6	92.6	7.1	0.3	7.4
S-3.9	89.1	8.2	2.7	10.9
S-4.3	89.0	10.4	0.6	11.0

TABLE 4: Polyphenolic contents of soluble fractions and corresponding aqueous and organic phases (S_{AF} and S_{EF}). in g/100g of solubles.

SAMPLE	POLYPHENOLS			YIELD OF EXTRACTION (%)
	S	S_{AF}	S_{EF}	
S-2.6	8.5	4.7	3.8	44.7
S-3.2	9.2	3.8	5.4	58.7
S-3.6	7.3	2.9	4.4	60.3
S-3.9	8.6	3.5	5.1	59.3
S-4.3	11.3	4.0	7.3	64.6

FIGURE 3

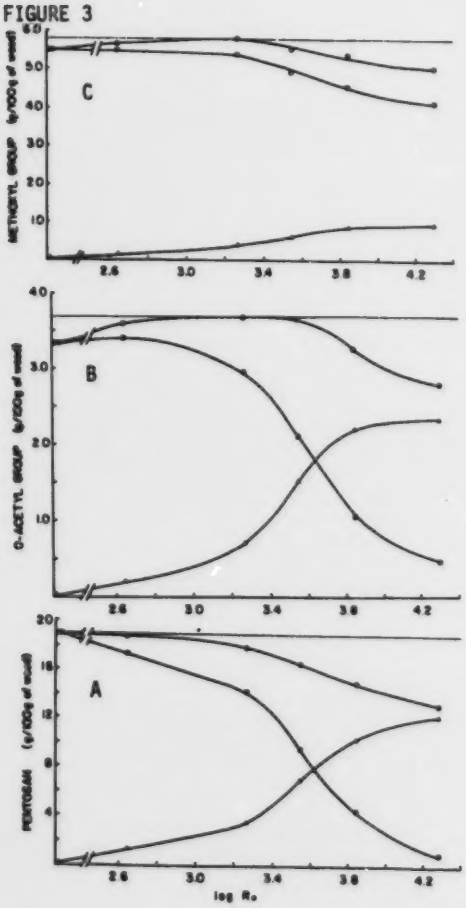
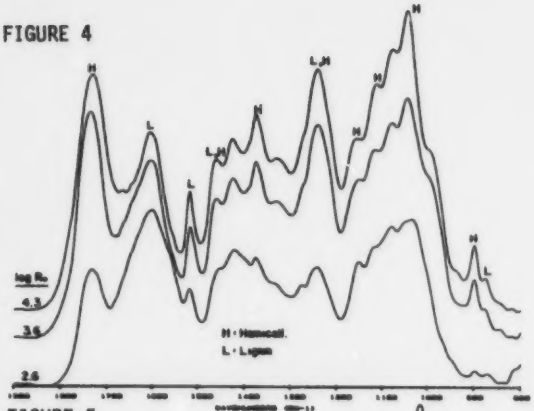


FIGURE 4



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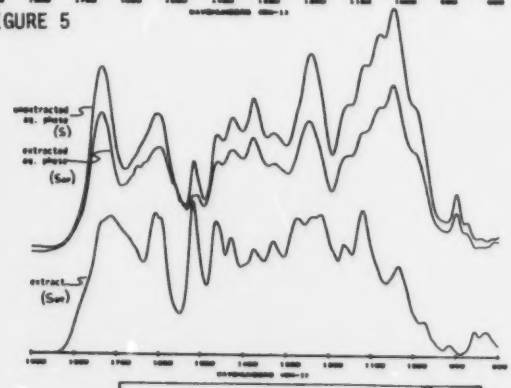

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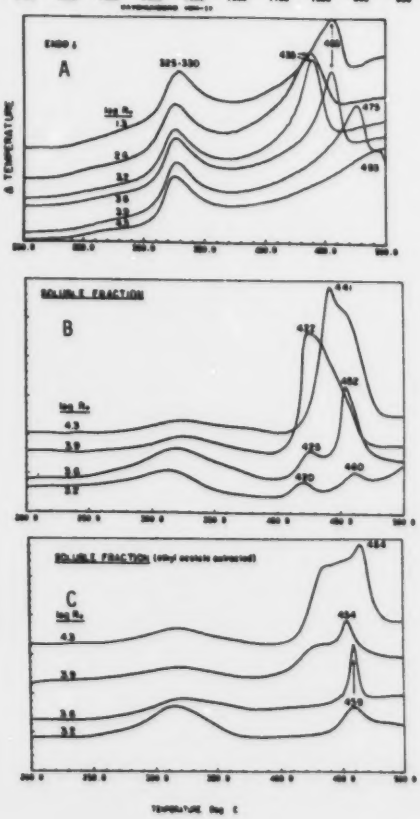

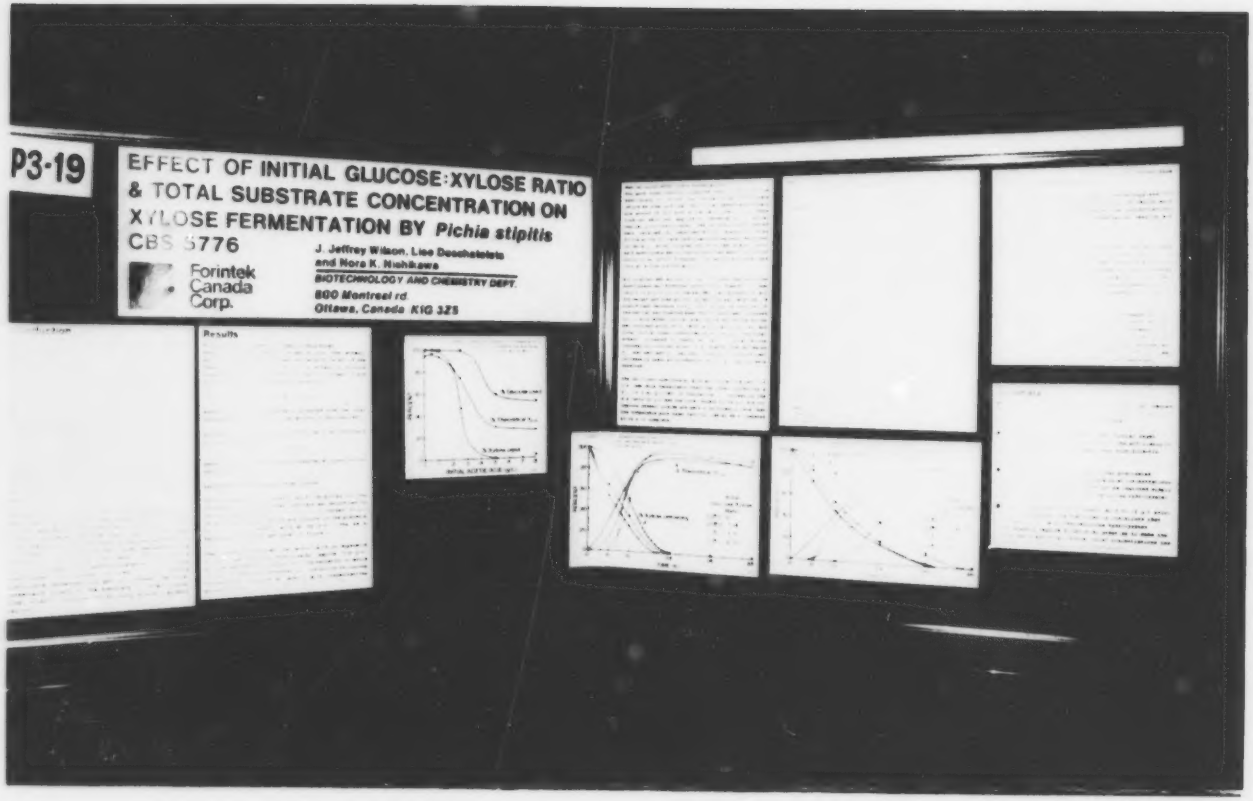
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EFFECT OF INITIAL GLUCOSE:XYLOSE RATIO & TOTAL SUBSTRATE CONCENTRATION ON XYLOSE FERMENTATION BY Pichia stipitis CBS 5776
Forintek Canada Corp.
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Results

EFFECT OF INITIAL GLUCOSE:XYLOSE RATIO AND TOTAL SUBSTRATE CONCENTRATION ON XYLOSE FERMENTATION BY *Pichia stipitis* CBS 5776

J. Jeffrey Wilson, L. Deschatelets and Nora K. Nishikawa

Forintek Canada Corp.

ABSTRACT

To increase the yield of ethanol from steamed-pretreated aspenwood hemicellulose hydrolysates, the effect of initial glucose:xylose ratio (G:X) and total initial substrate concentration (S_o) on ethanol yield from xylose ($Y_{p/x}$) was studied. Both pure sugar mixtures and hemicellulose hydrolysates were fermented by *Pichia stipitis* CBS 5776 with S_o ranging from 32 to 140 g/L and G:X between 0:1 and 2.2:1. For pure sugar fermentations, near theoretical $Y_{p/x}$ values of 0.44 to 0.46 g ethanol/g xylose supplied were obtained after 24 h from a S_o of 50 g/L and G:X ratio of 1:4 or 1:1. $Y_{p/x}$ from hemicellulose hydrolysates were highest for S_o < 35 g/L and G:X ratios near 1:4. Total xylose utilization was observed at higher S_o and G:X ratios , but $Y_{p/x}$ values were greatly reduced. These results suggest that when combining hemicellulose and cellulose hydrolysates from steam pretreated wood as a strategy for diluting the fermentation inhibitors associated with hemicellulose and increasing S_o, the resultant G:X ratio and S_o must be kept low enough to maximize ethanol production from xylose.

Dans le but d'accroître le rendement d'éthanol obtenu à partir d'hydrolysats d'hémicellulose de tremble pré-traités à la vapeur, on a étudié l'effet du rapport initial glucose:xylose (G:X) et de la concentration totale de substrat (S_o) sur le rendement de l'éthanol produit à partier du xylose ($Y_{p/x}$). Des mélanges de sucres purs et des hydrolysats d'hémicullulose ont été fermentés par *Pichia stipitis* CBS 5776, la valeur de S_o variant de 32 à 140 g/L et le rapport G:X étant compris entre 0:1 et 2.2:1. Dans le cas des fermentations du sucre pur, on a obtenu un $Y_{p/x}$ approchant de la valeur théorique, soit de 0,44 à 0,46 g d'éthanol/g de xylose fourni, aprés 24 heures, la valeur de S_o étant de 50 g/L et le rapport G:X étant de 1:4 au départ. La valeur obtenue pour $Y_{p/x}$ avec les hydrolysats d'hémicellulose était maximale lorsque S_o < 35 g/L, les rapports G:X sont approximativement de 1:4. Lorsque S_o et les rapports G:X étaient plus élevés, le xylose était totalement utilisé, mais les valeurs de $Y_{p/x}$ diminuaient de beaucoup. Ces résultats montrent que pour combiner des hydrolysats d'hémicellulose avec des hydrolysats de cellulose afin d'augmenter S_o et de diluer les inhibiteurs de la fermentation associés à l'hémicellulose, il faut maintenir faibles le rapport G:X et S_o, ce qui permet de maximiser la production d'éthanol à partir du xylose.

INTRODUCTION

For the economic production of ethanol from wood hydrolysates it is essential that the hemicellulosic sugars, in addition to the hydrolysed cellulose, be efficiently fermented. Separation of both hemicellulose and lignin from the cellulose following steam-pretreatment of aspenwood has been shown to benefit subsequent enzymatic cellulose hydrolysis[1]. In addition, the presence of lignin in steam-pretreated aspenwood has been shown to reduce enzymatic cellulose hydrolysis efficiency by adsorbing cellulases[2]. Consequently, the separation of steam-pretreated wood into its three major fractions, cellulose, hemicellulose and lignin, prior to enzymatic hydrolysis and fermentation is required to improve the utilization efficiency of the total pretreated wood[3].

When aspenwood is fractionated following SO_2-catalyzed steam-pretreatment, the water-soluble hemicellulose fraction, which is primarily hydrolysed acetylxylan, contains a mixture of sugars, mostly D-xylose, with some uronic acids and a significant quantity of acetic acid. The hydrolysates also contain sugar-degradation products such as furfural and hydroxymethylfurfural

and a variety of aromatic lignin-degradation products that are generated during the steam-pretreatment. These sugar- and lignin-degradation products, together with acetic acid, act synergistically to inhibit the fermentation activity of both bacteria and fungi[4,5,6,7,8,9]. The concentration of these water-soluble inhibitors in the hemicellulose hydrolysates makes fermentation to ethanol or other solvents more difficult.

The success of fermentation of the xylose in total hydrolysates of lignocellulosic substrates has been variable[10]. In our attempts to improve the ethanolic fermentation of our steam-pretreated aspenwood hemicellulose by the yeast, *Pichia stipitis* CBS 5776, we have found that rotoevaporation and ethyl acetate extraction treatments were able to remove the fermentation inhibitors from hemicellulose hydrolysates[9]. While rotoevaporation alone or steam-stripping[5,11] may be useful in removing acetic acid to non-inhibitory levels, the non-volatile inhibitors remain.

Intermittent feeding of cellulose hydrolysate to hardwood hemicellulose hydrolysate was shown to dilute inhibitors and improve ethanol yields using *Pachysolen tannophilus* when used with substrate containing <30 g/L total sugars[12]. However, the presence of excess glucose can repress xylose utilization[13].

In this study we have determined the inhibitory concentration of acetic acid on the fermentation of a mixed glucose and xylose substrate and the effect of the initial glucose:xylose (G:X) ratio and initial fermentable sugar concentration on the efficiency of xylose fermentation to ethanol. These results were part of a preliminary study to determine the feasibility of diluting the level of non-volatile inhibitors in hemicellulose hydrolysates with a cellulose hydrolysate (i.e. glucose) in order to both improve total fermentability and to increase the total fermentable sugars in the substrate for higher final ethanol concentration.

MATERIALS AND METHODS

Strain and Culture Conditions

Pichia stipitis CBS 5776 was obtained from the National Research Council of Canada (NRCC) culture collection as NRC 2893. Cultures were maintained on YPX slants containing 1% w/v yeast extract, 2% peptone, 2% xylose and 2% agar. Inocula were grown at pH 5.0 in YMPX broth containing 0.3% yeast extract, 0.3% malt extract, 0.5% peptone and 5.0% xylose for 48 h at 30°C and 150 rpm. Cells were harvested at 2000 g for 10 m and washed once in 0.1% peptone water prior to inoculation. Initial cell density for fermentation was approximately 10 g/L dry wt.

Substrate preparation

Aspenwood hemicellulose hydrolysate was obtained as the water-solubles following water-extraction of aspenwood chips that were pretreated with SO_2 and saturated steam at 200 or 210°C for 80 or 100 s as described elsewhere[14]. The dilute water-solubles were concentrated by rotoevaporation at 55°C to remove acetic acid, diluted to the appropriate solids concentration and adjusted to pH 5.0 with NH_4OH prior to fermentation.

Fermentation

All fermentations were carried out at 30°C in 50 ml volumes in 125 ml flasks fitted with foam stoppers, agitated at 150 rpm to provide the low aeration required for xylose fermentation. Fermentation medium contained 3 g/L yeast extract, 2 g/L diammonium phosphate. Ammonium hydroxide was used to adjust the pH to 5.0. D-Glucose and D-xylose were added as required after separate sterilization. D-Glucose was added to hemicellulose hydrolysates to increase the initial glucose:xylose ratio of the substrate as required.

Analytical

Acetic acid, ethanol, glucose, xylose, glycerol, and xylitol were analyzed by HPLC[15]. Dry weight determinations were done at 105°C for 16 h.

Ethanol Yield Calculations

The ethanol produced from glucose (P_g) was estimated based on 90% of the theoretical yield ($Y_{p/g}$) of 0.51 g ethanol/g glucose being obtained after total glucose utilization had occurred. This 90% yield estimate was based on several control glucose fermentations done under the conditions used in this study. The ethanol produced from xylose (P_x) was then estimated by subtracting P_g from the maximum ethanol produced from the total fermentable sugars (P_s). Therefore, the ethanol yield from xylose,

$$Y_{p/x} = (P_s - P_g)/X_o ,$$

where X_o is the initial xylose (g) in the substrate. Similarly, the ethanol yield from the total supplied sugars,

$$Y_{p/s} = P_s/S_o ,$$

where S_o is the initial total fermentable sugars in the substrate.

RESULTS AND DISCUSSION

Fermentation Inhibition by Acetic Acid

To determine the inhibitory concentration of acetic acid on the fermentation of mixed sugar substrate, the ability of *Pichia stipitis* to ferment 50 g/L of a 1:1 mixture of xylose and glucose was tested in the presence of 0 to 8 g/L acetic acid at pH 5.5 (48 h results shown in Fig. 1). The fermentation results indicated that <1 g/L acetic acid was not inhibitory to either glucose or xylose fermentation, with $Y_{p/s}$ exceeding 93% of the theoretical yield of 24 g ethanol/L. Above 1 g/L acetic acid, significant inhibition of xylose fermentation was observed, while inhibition of

glucose fermentation did not occur until the acetic acid concentration exceeded 2.5 g/L. At acetic acid concentrations above 2.5 g/L, glucose repression of xylose fermentation would also be in effect because glucose consumption was less than 100% after 48 h. Glucose fermentation occurred in the presence of 5 to 8 g/L acetic acid, although at a greatly reduced rate.

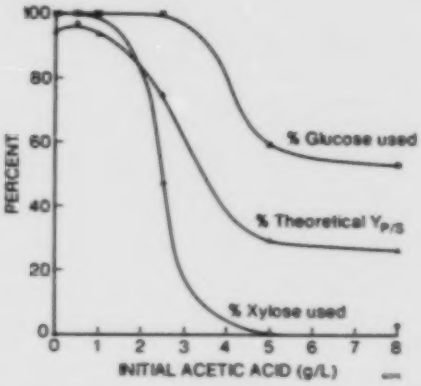

Figure 1. Acetic Acid Inhibition of Fermentation of 50 g/L of 1:1 Glucose:Xylose Mixture by *Pichia stipitis* After 48 h at pH 5.5

These results indicated that residual acetic acid in hemicellulose hydrolysates should be less than 1 g/L after rotoevaporation or steam-stripping for complete and rapid xylose fermentation. Similar results have been reported for inhibition of *Candida shehatae* xylose fermentation by acetic acid at 2.8 g /L, but not at 1.4 g/L at pH 5.5[5].

Effect of Glucose:Xylose Ratio and Total Fermentable Sugars on Xylose Fermentation

Despite treatments to remove acetic acid, the presence of non-volatile, lignin-derived inhibitors can still cause significant inhibition in hemicellulose hydrolysates containing 50 g/L total solids[9]. Because of this limitation we tested the feasibility of diluting hemicellulose hydrolysates with cellulose hydrolysate (i.e. glucose) to reduce the non-volatile inhibitor concentration while increasing the total fermentable sugars in the combined substrate. As a preliminary study, we determined the effect of increasing the glucose:xylose (G:X) ratio on the actual efficiency of xylose fermentation. Both pure sugar mixtures and glucose supplemented hemicellulose hydrolysates with G:X ratios of 0:1, 1:4 (similar to hemicellulose hydrolysates), 1:1 and 2.2:1 (similar to total wood hydrolysates) were tested at total fermentable sugar concentrations from 32 to 140 g/L (Table 1).

Pure Sugar Fermentations

From approximately 50 g/L total sugars, the theoretical ethanol yield from xylose ($Y_{p/x}$) of 0.46 g/g was obtained after 24 h using a substrate G:X ratio of 1:1. The other G:X ratios used also

Table 1. ETHANOL YIELDS FROM FERMENTATION OF DIFFERENT MIXTURES OF GLUCOSE AND XYLOSE BY *Pichia stipitis* CBS 5776

SUBSTRATE	GLU:XYL RATIO	TOTAL SUGARS (g/L)	ETHANOL (g/L)	$Y_{p/x}$ (a)	$Y_{p/s}$ (b)
PURE SUGARS	0:1	47	19.4	0.42	0.42
	0:1	77	30.6	0.40	0.40
	1:4	49	21.4	0.44	0.44
	1:4	78	31.1	0.39	0.40
	1:1	47	21.4	0.46	0.45
	1:1	79	32.1	0.37	0.41
	1:1	140	39.6	0.11	0.28
	2.2:1	47	20.6	0.42	0.44
	2.2:1	77	31.6	0.33	0.41
HEMICELLULOSE (c) HYDROLYSATES					
(210°C/80s)	1:5	37	12.7	0.32	0.34
SAME + GLUCOSE	1:1	64	22.4	0.25	0.35
SAME + GLUCOSE	2.4:1	135	39.0	0.08	0.29
(200°C/100s)	1:4	32	13.4	0.41	0.42
SAME + GLUCOSE	1:1	54	21.6	0.34	0.40
SAME + GLUCOSE	1.6:1	66	23.0	0.19	0.35

(a) Yield of ethanol from xylose, estimated based on 90% conversion of glucose present to ethanol.
(b) Yield of ethanol from total glucose and xylose in substrate.
(c) Water solubles from SO_2-pretreated aspenwood steamed for the indicated time and temperature. Hydrolysates were treated to reduce acetic acid to <1 g/L before fermentation.

produced in excess of 86% of the theoretical $Y_{p/x}$ value after 24 h (Fig 2). As expected, xylose consumption rate decreased with increasing G:X ratio, because of glucose repression of xylose fermentation. Very little ethanol consumption by *P. stipitis* was noticed during the 24 h following depletion of the sugar substrate. Recently, the continuous fermentation of 47.5 g/L of 1:3.75 G:X ratio by a flocculent strain of *P. stipitis* was reported, producing 19 g/L ethanol, which represents an estimated $Y_{p/x}$ of 0.39[16].

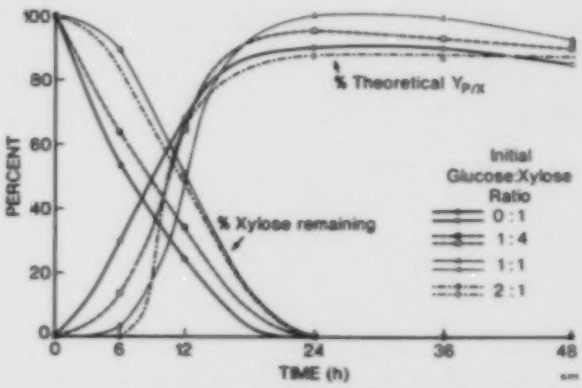

Figure 2. Ethanol Production from Xylose in 50 g/L Pure Sugar Substrates with Various Glucose:Xylose Ratios

From approximately 80 g/L total sugars, the theoretical ethanol yield from xylose was significantly decreased with all G:X ratios used (Fig 3). The G:X ratios of 0:1 and 1:4 produced around 84% of the theoretical $Y_{p/x}$ after a fermentation time of 36 h. Total xylose utilization was observed after 48 h using G:X ratios of 1:1 and 2.2:1, however the respective $Y_{p/x}$ values dropped to 0.37 and 0.33 g/g, or 80% and 70% of the theoretical value. The effect of increasing the total sugars was more pronounced when 140 g/L of 1:1 G:X ratio was fermented (Table 1). Total xylose and glucose utilization was observed after 72 h, however $Y_{p/x}$ was only 0.11 g/g or 24% of theoretical and $Y_{p/s}$ was only 0.28 g/g. Similar low $Y_{p/s}$ values of 0.31 and 0.27 g/g can be calculated from recently reported fermentation data for 145 g/L total sugars and G:X ratio of 1:1 using *P. stipitis* and *Candida shehatae* respectively, even though glucose addition was delayed for 24 h[13].

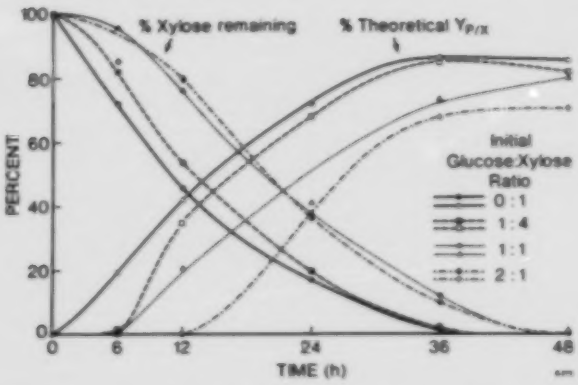

Figure 3. Ethanol Production from Xylose in 80 g/L Pure Sugar Substrates with Various Glucose:Xylose Ratios

The results of the pure sugar studies suggested that using cellulose hydrolysate to dilute the hemicellulose hydrolysate should be done such that the initial fermentable sugars are around 50 g/L with a G:X ratio of approximately 1:1. These findings were then applied to fermentation of actual hemicellulose hydrolysates.

Hemicellulose Hydrolysate Fermentations

Two different aspenwood hemicellulose hydrolysates were tested. The hydrolysates were obtained by water-extracting aspenwood chips following the SO_2-catalysed steam-pretreatments described in Table 1. Both hydrolysates were rotoevaporated to 20% total solids, at which point acetic acid concentration was <1 g/L. Each was then diluted with either water or glucose solution to obtain different G:X ratios with the same initial xylose concentration (equivalent to that present in 5% w/v total solids for each hydrolysate).

The 210°C/80s hemicellulose hydrolysate had an initial G:X ratio of 1:5. Total xylose fermentation occurred after 36 h, however $Y_{p/x}$ was only 0.32 g/g or 70% of theoretical. A 4 g/L cell dry wt increase and 0.85 g/L xylitol were also produced. Increasing the G:X ratio to 1:1 with glucose also increased the total sugars to 64 g/L. While 96% of the xylose was used in 36 h and the final ethanol concentration increased, the estimated $Y_{p/x}$ decreased to 0.25 g/g or 54% of theoretical. Increasing the G:X ratio to 2.4:1 and the total sugars to 135 g/L raised the final ethanol concentration to nearly 4% (w/v). Total xylose utilization was observed after 72 h, however none of the ethanol could be attributable to xylose fermentation, by our estimation method, and $Y_{p/s}$ was only 0.29 g/g. A 7.5 g/L cell dry wt increase and 2.7 g/L xylitol were also produced.

The 200°C/100s hemicellulose hydrolysate had an initial G:X ratio of 1:4 was more fermentable than the other hydrolysate producing a $Y_{p/x}$ of 0.41 g/g (89% of theoretical) and total xylose utilization after 48 h. Increasing the G:X ratio to 1:1 and the total sugars to 54 g/L did not improve the fermentation yields and were significantly less than the comparable pure sugar results, taking 96 h to complete compared to 24 h to complete. Increasing the G:X ratio to 1.6:1 to further dilute this hydrolysate did not produce any improvement in xylose fermentation rate or yield. These results suggest that further dilution of the non-volatile inhibitors was necessary. However, further dilution with glucose would increase the total sugars and G:X ratio to where $Y_{p/x}$ values near zero would be expected, based on the pure sugar studies discussed above.

CONCLUSIONS

These studies have shown that fermentation of SO_2-catalyzed steam-pretreated aspenwood hemicellulose hydrolysates at concentrations of 5 wt% total solids and above cannot be improved simply by dilution with glucose (i.e. cellulose hydrolysates). Despite the reduction of acetic acid to <1 g/L prior to fermentation, the non-volatile inhibitors that remain apparently require dilution so great as to make the G:X ratio and total sugar concentrations too high for efficient xylose fermentation as shown by the pure sugar fermentations.

Further studies are needed to better define the optimum steam-pretreatment conditions that would minimize lignin-degradation products in the hemicellulose hydrolysate or to develop a cost-effective inhibitor removal treatment that would permit efficient xylose fermentation in hydrolysates containing greater than 35 g/L total sugars.

ACKNOWLEDGEMENT

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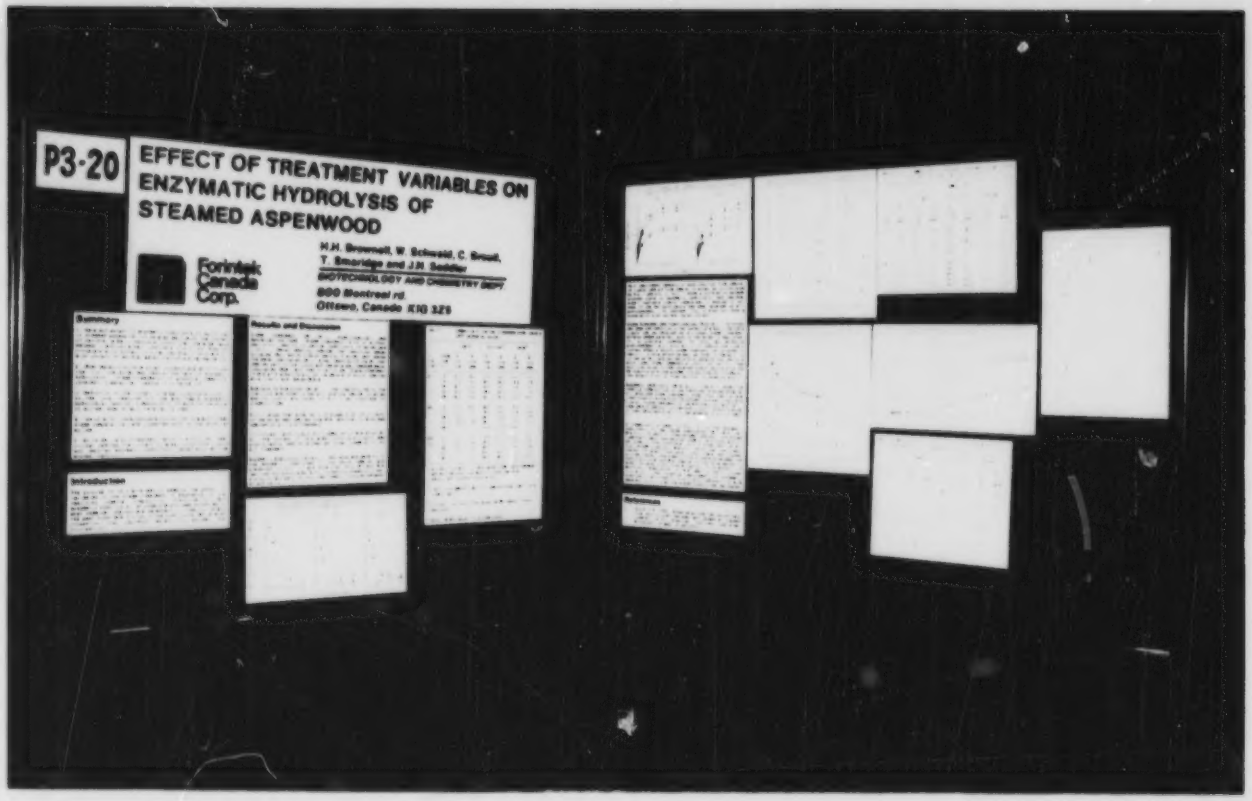
P3-20
EFFECT OF TREATMENT VARIABLES ON ENZYMATIC HYDROLYSIS OF STEAMED ASPENWOOD
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Summary
Results and Discussion
Introduction
References

EFFECT OF TREATMENT VARIABLES ON ENZYMATIC HYDROLYSIS OF STEAMED ASPENWOOD

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The effects of steaming time, temperature, SO_2 catalysis, and H_2O_2 post treatment, on chemical composition and enzymatic hydrolysis of aspenwood, have been determined. At 240° in the absence of SO_2, accessibility of cellulose increases with steaming time from 20 to 180 s. Recovery of xylan, however, decreases after times exceeding 80 s. Accessibility of cellulose, in the alkali-washed product, increases with H_2O_2 post treatment, which further decreases lignin content without altering xylan content. Glucose yield on enzymatic hydrolysis correlates well with alkali-insoluble lignin content between 1 and 15%, but not with xylan or total lignin contents, indicating that alkali-insoluble lignin controls accessibility in steamed aspenwood. Use of SO_2 catalysis permits the use of shorter steaming time at lower temperatures, and results in less destruction of xylan for the same degree of cellulose accessibility, while converting most of the solubilized xylan to monomeric xylose. Comparison of the enzymatic hydrolysis of the fractions, [water-insolubles (WI), water-and-alkali-insolubles (WIA), and H_2O_2-treated WIA (WIA/H_2O_2)] at four enzyme levels between 16.3 and 6.5 FPU/g of cellulose, showed little or no difference between WI and WIA whereas WIA/H_2O_2 gave significantly higher glucose yields, with the relative improvement increasing with decreased enzyme loading.

On a déterminé les effets de la durée du traitement à la vapeur, de la catalyse au SO_2 et du post-traitement au H_2O_2 sur la composition chimique et sur l'hydrolyse enzymatique du bois de tremble. À une température de 240°C et en l'absence de SO_2, l'accessibilité de la cellulose augmente avec la durée du traitement à la vapeur de 20 à 180 s. Toutefois, la récupération du xylanne diminue lorsque la durée de traitement dépasse 80 s. L'accessibilité de la cellulose dans le produit lavé avec un alcali augmente lorsqu'il y a post-traitement au H_2O_2 qui diminue encore plus la teneur en lignine sans modifier la teneur en xylanne. Il existe une corrélation étroite entre le rendement en glucose et la teneur en lignine insoluble dans les alcalis dans la plage de 1 - 15%; cependant, cette corrélation est inexistante entre le rendement en glucose et la teneur en xylanne ou la teneur en lignine totale, ce qui indique que l'accessibilité dans le bois de tremble est déterminée par la teneur en lignine insoluble dans les alcalis.
La catalyse au SO_2 permet de diminuer la durée du traitement à la vapeur et de réaliser ce traitement à de plus faibles températures; de plus, elle réduit, pour une accessibilité donnée, la quantité de xylanne détruite pendant le traitement et convertit la plupart du xylanne solubilisé en xylose monomérique. Si l'on compare l'hydrolyse enzymatique des fractions [matières insolubles dans l'eau (WI), matières insolubles dans l'eau et les alcalis (WIA) et matières insolubles dans l'eau et les alcalis et traitées au H_2O_2 (WIA/H_2O_2)] à quatre concentrations d'enzyme comprises entre 16.3 et 6.5 FPU/g de cellulose, on constate qu'il y a peu sinon aucune différence entre les WI et les WIA, tandis que le rendement en glucose est considérablement plus élevé dans le cas des WIA/H_2O_2, l'amélioration relative augmentant au fur et à mesure que l'apport en enzyme diminue.

SUMMARY

1) Rate and extent of enzymatic hydrolysis of cellulose, in steamed aspenwood, correlates well with the content of residual alkali-insoluble lignin over the wide range between 1 and 16% alkali-insoluble lignin, but does not correlate with content of total residual lignin and not with content of residual water-insoluble xylan below 11%.

2) When water-insoluble-xylan contents are much higher than 11%, the xylan may reduce the rate of enzymatic hydrolysis. Steam treatments of possible commercial interest, however, all reduce it to below 11%.

3) Reduction of the content of alkali-insoluble lignin, to the level required for the most rapid enzymatic hydrolysis, results in destruction of much of the xylan or xylose, when no acid catalyst is used.

4) Use of an SO_2 catalyst permits the use of a much lower steam temperature, and conserves most of the xylan as xylose.

5) An oxidative posttreatment (with or without SO_2 use) further reduces the content of alkali-insoluble lignin and improves enzymatic hydrolysis, especially at low enzyme loadings.

INTRODUCTION

The purpose of this work was to examine the effect of variables in the steam treatment of aspenwood, on the resulting chemical composition, fractionation, and enzymatic hydrolysis. An understanding was sought as to what chemical changes are necessary in order to obtain the best substrate for cellulose hydrolysis, while also conserving the byproduct xylan, or xylose, for utilization.

RESULTS AND DISCUSSION

Steam Treatment (No SO_2), Fractionation, and Abbreviations Used. Steam treatment, with or without explosion, results in partial hydrolysis of xylan and lignin. Water washing removes the resulting water solubles (WS), which consist mainly of xylan, and leaves the water insolubles (WI). Alkali washing of the WI then removes part of the lignin and leaves alkali-washed water insolubles (WIA), enriched in cellulose. A posttreatment of WIA with alkaline H_2O_2 by the method of Gould[1] removes more lignin and leaves WIA/H_2O_2.

Analysis of Fractions (No SO_2). The compositions of the fractions are shown in Table 1, and the removal of xylan and of lignin are shown in Fig. 1 as functions of steaming time.

Fig. 1 shows that after 80 s of steaming at 240°C, most of the xylan was removed from WIA, and that no more was removed by H_2O_2 posttreatment.

Table 1. Composition of Fractions of Aspenwood Steam-Treated at 240°C, Without SO_2 Catalyst

Fraction[1]	Steam time (s)	Lignin[2] % fraction	Lignin[2] % orig. wood	Cellulose[3] % fraction	Cellulose[3] % orig. wood	Xylan[4] % fraction	Xylan[4] % orig. wood
WI	20	25.3	19.0	57.4	43.1	12.1	9.1
	40	27.6	21.4	60.1	46.6	8.8	6.8
	80	30.7	21.2	62.5	43.1	3.0	2.1
	120	32.6	22.5	58.6	40.5	1.4	1.0
	180	36.0	25.6	56.1	39.9	<1.0	<0.7
WIA	20	17.2	10.5	66.6	40.5	9.3	5.7
	40	13.9	7.7	78.0	43.4	6.8	3.8
	80	9.0	4.5	84.4	42.6	1.7	0.9
	120	3.9	1.8	90.1	41.6	1.0	0.5
	180	2.4	1.1	91.9	41.9	<0.6	<0.3
WIA/H_2O_2	20	13.2	7.5	72.9	41.7	11.3	6.5
	40	10.9	5.8	78.0	41.4	6.8	3.6
	80	4.8	2.4	83.1	41.1	1.6	0.8
	120	2.4	1.1	87.7	40.5	1.4	0.6
	180	1.1	0.5	85.0	38.5	0.6	0.3

1 WI: water insolubles, i.e. water-washed steam-treated aspenwood
WIA: water-and-alkali insolubles, i.e. alkali-washed WI
WIA/H_2O_2: WIA treated with alkaline H_2O_2

2 Lignin: total apparent lignin (i.e. apparent Klason lignin + acid-soluble lignin)

3 Cellulose: cellulose or other glucan, by HPLC analysis of acid hydrolysate

4 Xylan: by HPLC analysis of acid hydrolysate

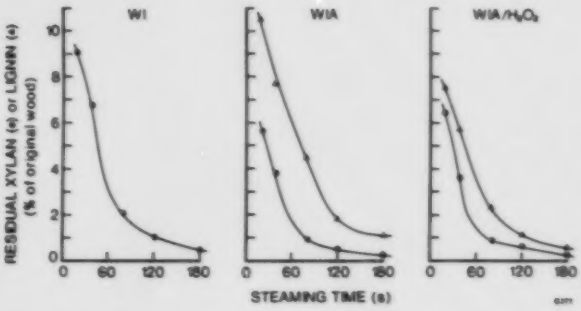

Fig. 1 Effect of treatment time in steam at 240°C on residual contents of xylan and total apparent lignin in aspenwood after water washing (WI), alkali washing (WIA), and H_2O_2 treatment (WIA/H_2O_2)

In contrast, much lignin still remained in WIA after 80 s. The content of this alkali-insoluble lignin was significantly reduced either by longer steaming or by H_2O_2 treatment.

Enzymatic Hydrolysis (No SO_2). The rates and extents of the enzymatic hydrolyses of the above

samples are presented in Fig. 2, and show that both WI and WIA improved as substrates with increasing steaming time. A significant part of this improvement occurred between 80 and 180 s.

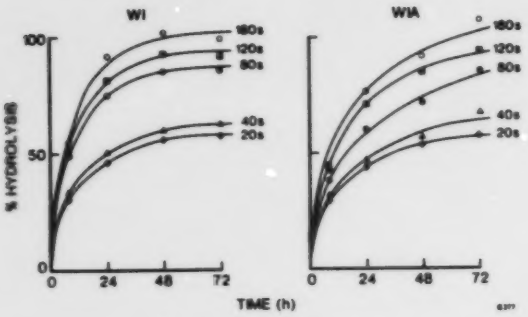

Fig. 2 Effect of treatment time in steam at 240°C on enzymatic hydrolysis of cellulose in aspenwood after water washing (WI) and after alkali washing (WIA)

This improvement appears to have resulted from removal of lignin, and not from removal of xylan, as is indicated by Fig. 3 and Fig. 4. Fig. 3 shows a correlation between glucose yield on enzymatic hydrolysis, and residual alkali-insoluble lignin, regardless of whether or not some of the delignification had been obtained by H_2O_2 posttreatment. In contrast, Fig. 4 does not show a correlation with residual xylan content.

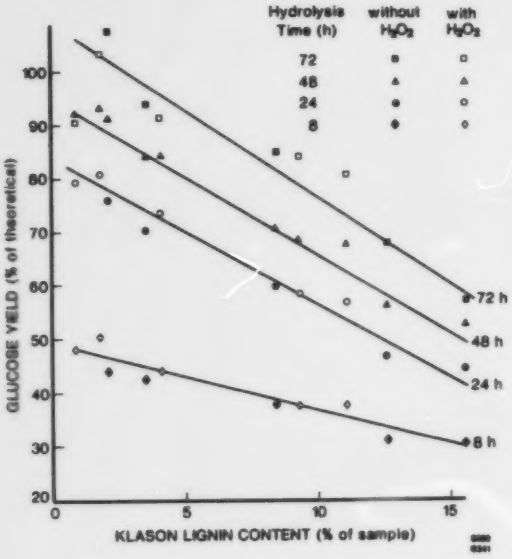

Fig. 3 Relationship between apparent Klason lignin content of water-and-alkali-washed steam-heated aspenwood, with or without subsequent treatment with H_2O_2, and the glucose yield obtained on enzymatic hydrolysis

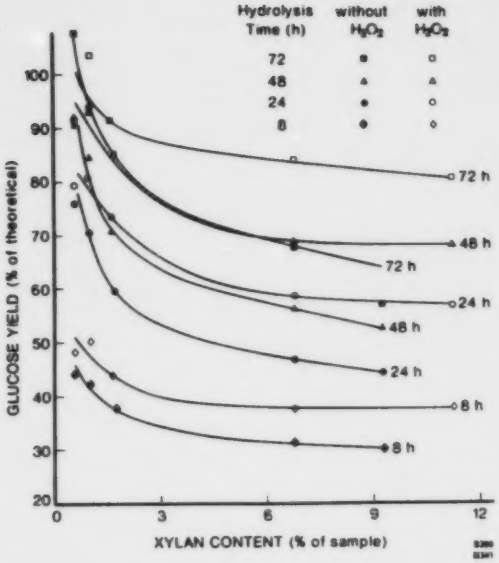

Fig. 4 Glucose yield obtained on enzymatic hydrolysis of steam-heated, water-and-alkali-washed aspenwood, both before and after secondary treatment with H_2O_2, plotted against residual xylan content of the sample

<u>Steam Treatment and Fractionation (With SO_2)</u>. Although the required reduction in the content of alkali-insoluble lignin can be obtained by prolonged steam treatment without added catalyst, much of the xylan is destroyed. It is possible, however, by using an oxidative posttreatment (e.g. with H_2O_2), to reduce the lignin content after a shorter steam treatment, as is shown in Table 1. A more effective way, as shown in Table 2, is to use an SO_2 catalyst which also permits the use of a much lower steam temperature (200°C vs 240°C). The surviving xylan is then obtained almost entirely in the WS fraction as xylose monomer (rather than as oligomers). The effect of SO_2 on xylan survival is shown in Fig. 5.

Table 2. Composition of Fractions of Aspenwood Steam-Treated at 200°C for 100 s, <u>With</u> SO_2 Catalyst

		Composition					
		Lignin		Cellulose		Xylan	
Fraction	SO_2 % orig. wood	% fraction	% orig. wood	% fraction	% orig. wood	% fraction	% orig. wood
WI	0.5	30.9	19.8	60.4	38.7	4.1	2.6
	1.0	31.7	19.7	62.6	39.0	1.2	0.8
	1.6	32.5	19.8	62.6	38.2	1.1	0.7
	2.5	32.9	19.9	62.4	37.8	0.9	0.5
	5.0	33.5	19.6	60.9	35.7	0.7	0.4
WIA	0.5	6.9	3.2	90.1	41.3	2.7	1.3
	1.0	2.1	0.9	94.9	40.1	1.2	0.5
	1.6	1.8	0.7	95.1	39.1	0.9	0.4
	2.5	1.6	0.6	95.9	38.1	0.8	0.3
	5.0	1.7	0.6	95.7	36.8	0.7	0.3

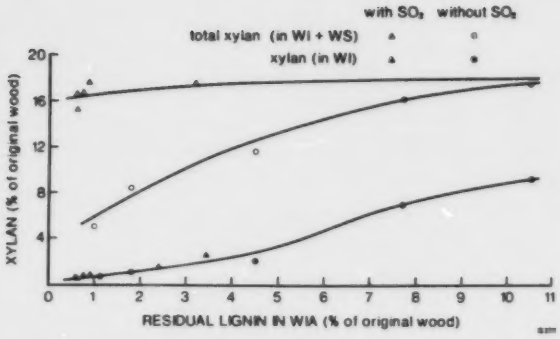

Fig. 5 Effect of SO_2 on removal and survival of xylan (or xylose), as functions of residual alkali-insoluble-lignin content

<u>Enzymatic Hydrolysis (With SO_2)</u>. Table 3 shows the chemical compositions of the fractions obtained after an SO_2-catalyzed steam treatment, under less than optimum conditions for minimizing the content of alkali-insoluble lignin. A posttreatment of the WIA fraction, with H_2O_2, then gave a reduction in residual lignin content similar to that obtained by H_2O_2 in the absence of SO_2 in Table 1.

Table 3. Composition of Fractions of SO_2-Catalyzed Steam-Treated Aspenwood[1] Used in Enzymatic Hydrolysis of Fig. 6.

	Lignin[2]		Cellulose[3]		Xylan[3]	
Fraction	% fraction	% orig. wood	% fraction	% orig. wood	% fraction	% orig. wood
WI	30.3	18.7	68.3	42.1	0.64	0.39
WIA	5.4	2.3	92.4	40.0	0.67	0.29
WIA/H_2O_2	2.2	0.9	94.6	39.8	0.73	0.31

1 Original wood: lignin 22.7, cellulose or other glucan 43.2, xylan 21.9%

2 Lignin: total apparent lignin (apparent Klason lignin + acid-soluble lignin)

3 By HPLC analysis of acid hydrolysate

A comparison is made, in Fig. 6, of the enzymatic hydrolysis of the three substrates (WI, WIA, and WIA/H_2O_2), at each of three enzyme loadings. The enzyme loadings in each case were per gram of cellulose, and not per gram of total substrate. Fig. 6 shows that, at all four enzyme loadings, WIA/H_2O_2 (which had the lowest content of alkali-insoluble lignin) gave the highest glucose yields. There was little difference between the hydrolysis of WI and WIA, removal of the large amount of alkali-soluble lignin from WI having little effect. If anything, hydrolysis of WIA was slightly slower initially. The relative improvement in enzymatic hydrolysis, as a result of H_2O_2 posttreatment, is more apparent in Fig. 6 as the enzyme loading was decreased.

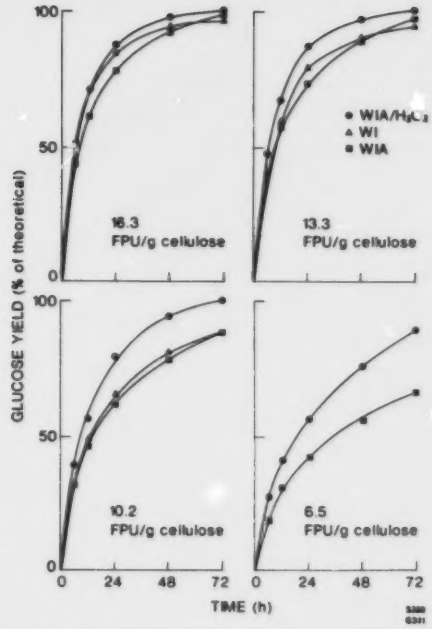

Fig. 6 Effect of enzyme loading (Novozyme-Celluclast) on hydrolysis of SO_2-catalyzed steam-heated aspenwood (1.6 SO_2, 120 s/210°C), after water washing (WI), water-and-alkali washing (WIA), and water-and-alkali washing followed by H_2O_2 treatment (WIA/H_2O_2)

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P3-21

Development of a Hydrogen Fluoride Wood Hydrolysis Process for the Production of Ethanol from Cellulose

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Background

Process Development Unit

DEVELOPMENT OF HYDROGEN FLUORIDE WOOD HYDROLYSIS PROCESS FOR THE PRODUCTION OF ETHANOL FROM CELLULOSE

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Wardrop investigated the production of ethanol from wood through HF-wood hydrolysis. A process development unit was built and operated to continuously adsorb vapour HF onto wood chips, producing hydrolyzates with very high sugar yields. Mechanical difficulties due to corrosion and plugging were substantially reduced but not eliminated. Based on operating experiences appropriate modifications were suggested to further enhance operating reliability and safety.

Wardrop a étudié la production d'éthanol à partir de bois par hydrolyse avec de l'acide fluorhydrique. Elle a construit une unité de mise au point du procédé qui permet d'absorber continuellement de la vapeur de HF sur les copeaux de bois dans les conditions de réaction appropriées, puis de récupérer et de recycler le HF. Des difficultés mécanique, à cause de la corrosion ont été substantiellement réduit mais pas éliminé. Selon les résultats de ces travaux, on a élaboré le plan d'une usine pilote en vue d'améliorer encore plus le procédé.

BACKGROUND

The use of hydrogen fluoride or HF has been recognized as a potential means of achieving efficient conversion of ligno-cellulosics to monomer sugars that can be subsequently fermented to produce ethanol. A generalized schematic for the conversion of cellulose to ethanol employing vapour phase HF is provided in Figure 1.

Hydrogen fluoride is a strong halide acid, with unique characteristics. The mode of action of HF on cellulose is not a true hydrolysis, as in the case of other mineral acids or cellulose enzymes, but more of a solubilization or so-called "solvolysis". Adsorption of HF causes the breakdown of crystalline cellulose. When HF is subsequently desorbed, there is a repolymerization into simple oligomers, which themselves can be converted to constituent sugar monomers using very mild conventional acid hydrolysis conditions [1].

The potential of vapour phase HF treatment of wood chips for efficient production of ethanol was recognized by the crown corporation Canertech, who initiated research on HF processing in 1983 [2]. This work has been carried forward under the auspices of the department of Energy, Mines and Resources.

For the past three years, Wardrop Engineering Inc., has been responsible for coordinating the latest research project, which has centered on the design, construction and operation of a Process Development Unit (PDU) for the continuous treatment, or primary hydrolysis, of aspen wood chips with HF vapour.

The original objectives of this project have been described previously [3]. This paper presents an update of progress and final results.

PDU DESIGN

The design concepts incorporated in the PDU included:

- Plug flow movement of chips by use of piston conveyors.
- Separate adsorption and desorption reactors with isolation provided by knifegate valves.
- Countercurrent flow of the HF-carrier gas mixture and the wood chips.
- Continuous recycle of HF, being removed from the desorber and readsorbed in the adsorber.

The original design of the PDU involved an inclined (30°) adsorber reactor and a horizontal desorber. Both reactors were 8 inch diameter mild steel tubes with polyethylene liners, while the transter chute connecting the two reactors was 4 inches in diameter.

Commissioning of this unit was delayed by extensive mechanical difficulties, primarily related to plugging and corrosion. As a result a modification and simplification of the PDU was undertaken.

PDU MODIFICATION

The modified PDU configuration is illustrated in Figure 2. The modifications included:

1. Shortening the adsorber reactor and remounting it to a

horizontal position.

2. Shortening the transfer chute between the reactors and expanding to 8 inch diameter.

3. Simplification of the gas piping network.

In the modified PDU, aspen chips were loaded into the feed tank, then pushed through the adsorber where they were contacted with HF vapour. The HF loaded chips then dropped through the transfer chute, and were finally pushed through the desorber reactor where HF was removed to the preheated carrier gas. The PDU had an estimated solids residence time of between six and seven hours.

PDU OPERATION

The modification of the PDU dramatically reduced the incidence of mechanical difficulties during operation. In its modified configuration the PDU was operated in excess of 220 hours contacting wood chips with HF gas, and a series of five long experimental runs were conducted in which the duration of operation was progressively improved from approximately 30 hours to over 50 hours.

During these operations approximately 230 kg of aspen wood chips between 1/4" and 3/8" size were fed to the reactor, and over 130 kg of treated chips, or primary hydrolyzate, was recovered.

The combined yield of hexose and pentose sugar monomers derived from recovered hydrolyzates varied from approximately 60 percent to over 90 percent, which was obtained in one run. During this one run, as illustrated in Table 1, a combined sugar yields of well over 80 percent was attained for a sustained period of operation. These very high yields could not be reproduced in subsequent experiments, as a result of mechanical difficulties.

One of the goals of PDU operation was the recycle of HF from the desorber for readsorption in the adsorber reactor. Although corrosion caused by the HF limited the ability to accurately control the HF content of the carrier gas, various observations did suggest that HF gas was being recycled back to the desorber reactor.

The adsorber HF loading levels were observed to rise sharply on occasion, requiring the reduction of make-up HF fed to the system. This phenomenon was thought to be due to HF recycling. Also, during one run, as illustrated in Figure 3, the gas HF content in the adsorber cycled through a maximum. Sequential peaks in the adsorber outlet, and then the desorber outlet suggested HF recycle.

Corrosion caused by HF was dealt with to a great extent, but was still a recurrent problem. The mild steel reactors were relatively unaffected by vapour HF, especially with the installation of an inert polyethylene liner. However, the presence of highly corrosion HF-water condensates caused severe corrosion to certain components, especially the adsorber inlet gas piping network. Corrosion necessitated continuous maintenance, such as the frequent replacement of couplings, seals and other components.

Mechanical difficulties associated with HF unfortunately continued to hamper operations, preventing the achievement of sustained steady state. The major obstacles encountered during operations are summarized as follows:

1. Plugging of chips in the reactors or transfer chute.

2. Collapse of chips into a sticky, semi-solid mass which exacerbated plugging problems, and severely limited mass transfer in the bed.

3. Corrosion of certain components exposed to HF-water condensates.

4. Gas HF concentration control limitations.

5. Substantial residual of HF in treated chips, which was deemed to have resulted because of mass transfer limitations.

SAFETY ASPECTS

HF is well recognized as a hazardous chemical, both from environmental and occupational safety perspectives, because of its aggressively corrosive nature. Thus special precautions had to be undertaken to ensure its safe use. These included locating the PDU within a controlled ventilation, isolation enclosure, and the use of special protective clothing and equipment by operators.

DISCUSSION

The hydrolysis of cellulose by the use of vapour HF has already been shown to be a technique capable of producing extraordinarily high sugar yields, but also one which poses challenges for process operation and operating personnel.

The PDU continuously produced hydrolyzates with sugar yields generally over 60 percent and in one run consistently over 80 percent. These values compare very favourably to conventional acid hydrolysis processes with maximum yield values of near 60 percent and where yields of 25 to 50 percent are more typical.

During the course of experimentation, substantial experience was obtained in overcoming the mechanical and operational difficulties associated with HF. Based on this experience appropriate modifications were suggested for the redesign of the PDU that would further enhance operational reliability and safety. An updated conceptual pilot plant design was also prepared for further development of the process.

CONCLUSION

The hydrolysis of cellulose by the use of HF has continued to show promise as a means of producing extremely high yields of fermentable sugars from cellulosic materials. Further development will require the solution of a variety of mechanical and operational challenges, as well as attention to ensuring a high degree of environmental and occupational safety.

ACKNOWLEDGMENTS

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TABLE 1

ESTIMATED SUGAR YIELD FOR EXAMPLE RUN

Sample Time	Peak HF Loading[1]	Sugar Produced g/g Hydrolyzate Glucose	Xylose	Overall Sugar Yield
Day 2 10:05	108	.294	.096	76.9
20:15	83	.222	.078	68.1
21:55	83	.215	.080	66.4
23:35	103	.264	.080	74.8
Day 3 01:15	44	.288	.101	72.4
02:55	44	.294	.106	79.1
04:35	44	.312	.910	80.3
06:15	97	.352	.114	83.5
a 07:55	93	.368	.132	91.9
b 07:55[2]	93	.368	.132	86.9
09:00	89	.344	.116	89.1
Day 4 17:15	89	.374	.128	83.2
Day 7 12:15	89	.382	.126	82.1
16:22	89	.406	.133	82.6

NOTES:

1. Estimate based on Adsorber HF mass balance using estimated residenced time of 6.5 hours.

2. HF residual of 15.1% in product by water extraction employed in yield calculation.

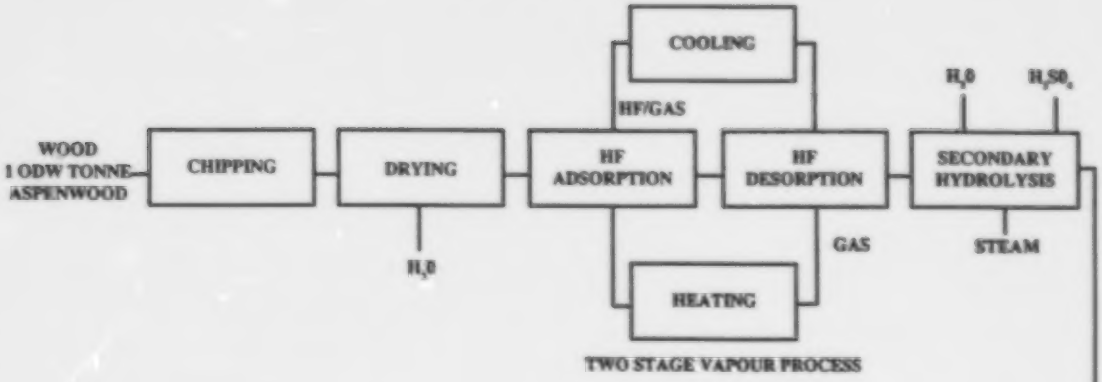
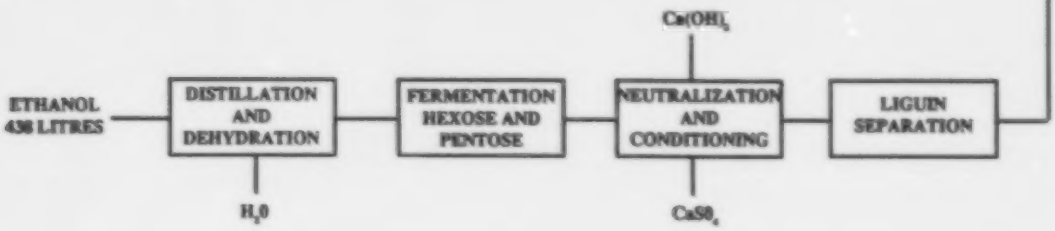


Figure 1. Schematic Block Diagram of HF - Wood Process



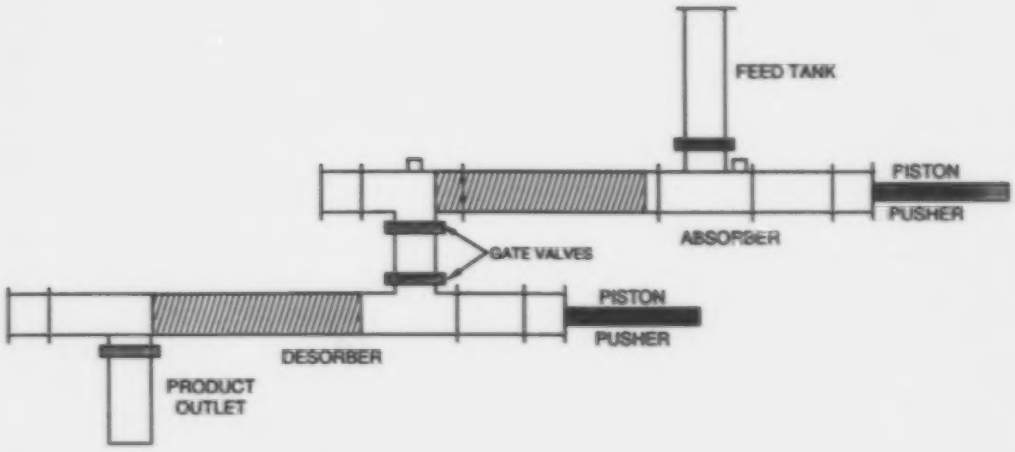


Figure 2 Modified PDU Configuration

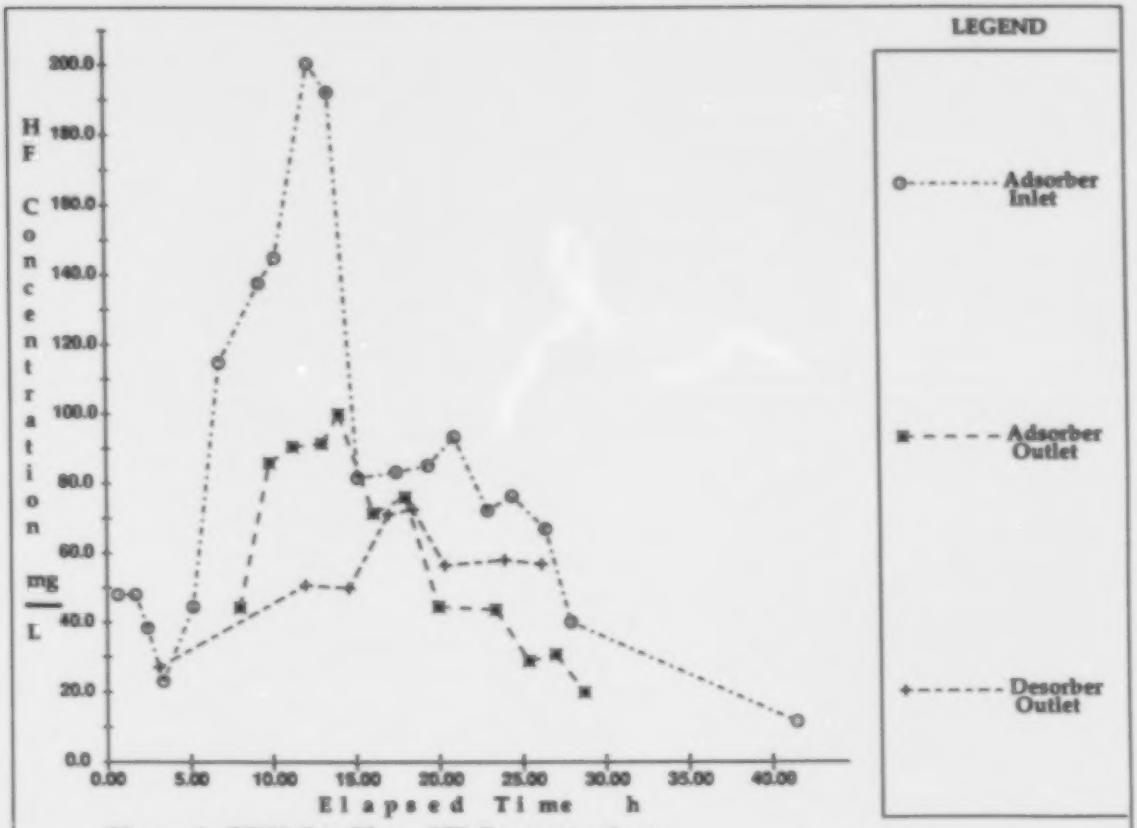
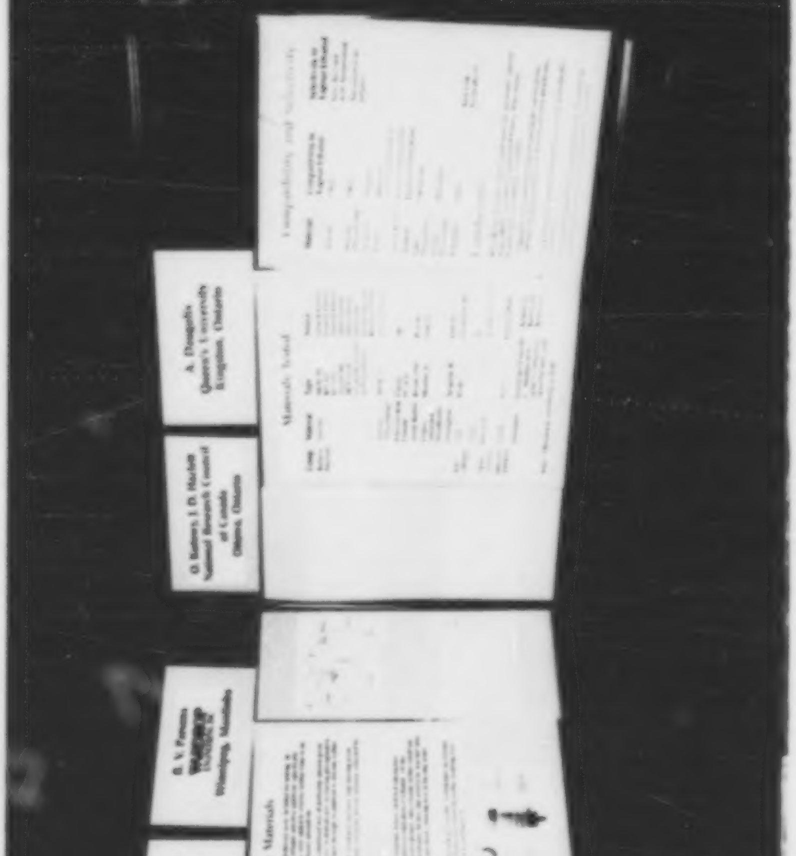


Figure 3. PDU Gas Phase HF Concentrations


P3-22
Development of an
Energy Efficient Membrane
Recovery System Suitable
for Ethanol from
Cellulose Recovery
Membrane Materials

DEVELOPMENT OF AN ENERGY EFFICIENT MEMBRANE RECOVERY SYSTEM SUITABLE FOR ETHANOL FROM CELLULOSE PROCESSES

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A study was conducted to investigate selectivity of semi-permeable membranes to ethanol in the vapour phase, in order to develop a novel and energy efficient process to recover ethanol from dilute solutions. A number of polymeric materials were tested, however, acceptable ethanol selectivity could not be obtained. The incorporation of ethanol selective extractants and organo selective zeolites also did not produce any significant selectivity to ethanol.

On a étudié des membranes semi-perméables filtrant sélectivement l'éthanol en phase vapeur, afin de mettre au point une nouvelle méthode consommant peu d'énergie pour récupérer l'éthanol à partir de solutions diluées. Plusieurs Polymère matériaux ont été testés, mais aucun des matériaux testés était suffisamment sélective à l'égard de l'éthanol. Le fait d'incorporer des agents d'extraction sélectives n'a pas non plus permis d'obtenir une sélectivité importante à l'égard de l'éthanol.

BACKGROUND

In the production of ethanol from biomass via fermentation, the purification of the ethanol product is an important consideration. The standard technology available is distillation, which, although well established, is very sensitive both in terms of capital cost and energy requirements to the concentration of ethanol in the feed, and is limited by the presence of a low boiling point azeotrope.

Membrane processes, unlike distillation, exploit selective adsorption and selective transport of molecules, relying on pressure rather than temperature as the driving force. Membrane processes have been viewed in general as means of achieving more energy efficient separation of ethanol and water.

OBJECTIVE

In an attempt to reduce energy requirements for separation, this study was undertaken to investigate a novel use of membranes for the selective recovery of ethanol. This approach involved:

1. Development and use of membranes to be selective to ethanol from water, concentrating ethanol in the membrane permeate.

2. Operation of membranes with the feed stream in the vapour phase.

This study focused on the testing of various potential membrane polymer materials to screen for selectivity to vapour phase ethanol. In a further attempt to enhance selectivity, the addition of selective agents to silicone rubber films was also investigated.

NOMENCLATURE

The term employed to characterize separation in this study was the dimensionless "α" separation factor, also termed "Selectivity", which is defined as follows:

$$\alpha_{ij} = \frac{(y_i/y_j)}{(x_i/x_j)}$$

where: x = fraction of component in feed
y = fraction of component in permeate
i,j = respective components

EQUIPMENT

The testing of membrane materials for selectivity to ethanol was conducted at the laboratories of the National Research Council of Canada in Ottawa, using two special membrane test cells. A smaller test cell with available membrane area of 10.7 cm^2 was constructed by modifying a standard static membrane cell. This cell, as illustrated in Figure 1, was

employed for the majority of testing. A larger test cell with available membrane area of 352 cm^2 was also employed.

The flow arrangement employed for the small cell is illustrated in Figure 2, with a similar arrangement employed for the second cell. Feed mixtures of ethanol and water were recirculated from a feed tank and evaporated prior to entering the cell by use of heating coils in a controlled temperature oil bath. Vapour exiting from the cell was condensed and returned to the feed tank.

A vacuum was maintained on the back side of membranes during test runs. Permeate samples were collected in cold finger tubes immersed in liquid nitrogen.

Cell temperature was monitored by use of an inserted thermocouple, while pressure was monitored by use of a pressure gauge located close to the cell. The vacuum on the back side of the membrane was monitored using either a gauge or mercury monometer.

In order to assess the effect of ethanol exposure on membrane integrity, nitrogen permeation tests (flux rates) were conducted at 100 psig and room temperature using a bubble meter both before and after tests runs.

ANALYSIS

The initial concentration of feed samples was made up to predetermined compositions. Feed, permeate, and non-permeate samples were collected during runs and measured using either a standard refractometer or gas chromatography method.

MEMBRANE MATERIALS

Polymer materials included in the testing are identified in Table 1. Some of these materials, as indicated, were obtained as membrane sheets. For the remainder, either thin dense or asymmetric films were made by dissolving or diluting the polymer in an appropriate solvent, casting onto a clean glass surface using a circular profile casting bar, and either drying or immersing in non-solvent in the case of asymmetric membranes.

Two types of ethanol selective additives, specifically zeolite and extractants, were added to silicone rubber films in an attempt to enhance ethanol adsorption. These materials were mixed to a desired proportion with the liquid silicone rubber prepolymers and then cast into a film.

The zeolite employed was a high silica version, which exhibits organophilic behaviour. This material was of particular interest given recently reported success in dramatically increasing pervaporative selectivity toward ethanol through addition of organophilic zeolite to silicone rubber [1].

A representative series of ethanol selective, high boiling point solvents were also chosen using the solvent database compiled by Queen's University [2]. The operating conditions within the membrane were approximated and a computer run conducted to rank the solvents in the database according to their relative selectivity to ethanol. Three of the four extractants tested were from the top ten compounds, as indicated in Table 1.

EXPERIMENTAL RESULTS

None of the polymer materials tested exhibited satisfactory performance for the selective separation of ethanol. Two major problems were apparent, namely materials incompatibility and lack of sufficient selectivity. The results for the materials tested are summarized in Table 2.

The problem of materials incompatibility was severe. Udel polysulfone, which is commonly employed for asymmetric membranes, was completely shattered by exposure to vapour ethanol. Victex polysulfone and various rubbery polymers were also adversely affected, as evidenced by a substantial increase in nitrogen permeation.

Of the materials that withstood exposure, only silicone rubber, polydimethylsiloxane, exhibited any selectivity toward ethanol, and this selectivity was found to be dependent on both feed concentration and temperature. For feed solutions at the azeotropic concentration, no perceivable separation was detected for the films tested, regardless of the temperature. For feed solutions near 50 wt%, as illustrated in Figure 3, silicone exhibited some selectivity toward ethanol. The selectivity, however, was found to generally decline as the temperature was increased to the extent that membranes crossed over to becoming water rather than ethanol selective.

The addition of ethanol selective zeolite or extractants to silicone rubber also did not enhance the selectivity of the resulting films toward ethanol. As illustrated in Figures 4 and 5 respectively, films incorporating zeolites or extractants produced results no better than silicone alone, and well below comparable vapour liquid equilibrium.

DISCUSSION

The objective of the study, to attempt to develop an ethanol selective membrane system, was not fulfilled because satisfactory selectivity to ethanol in the vapour phase could not be achieved.

Of the polymers tested only silicone rubber produced any selectivity toward ethanol. Even in this case selectivity was not sufficient, and was also found to be both concentration and temperature dependent sufficient selectivity could not be achieved even through the use of very hydrophobic polymers.

Attempts to induce ethanol selective behaviour by the addition of selective zeolite and extractant agents, also did not produce any desired selectivity enhancement. This contrasted with substantial enhancement in pervaporation processes.

CONCLUSIONS

While the results of this study cannot preclude successful vapour phase ethanol concentration using membranes, three major obstacles were encountered. These are listed as follows:

1. Aggressive environment of high temperature vapour phase ethanol resulting in destruction of some polymer membranes.

2. Lack of selectivity toward ethanol by even very hydrophobic polymers.

3. Concentration and temperature dependencies of selectivity working against the selective concentration of ethanol.

Although no satisfactory selectivity was achieved for the separation of ethanol from water in vapour phase, the results of this study may cast some light on the mechanisms of vapour phase transport.

ACKNOWLEDGMENTS

Financial support from the Bioenergy Development Program is gratefully acknowledged.

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TABLE 1

SUMMARY OF MATERIALS INCLUDED IN TESTING

Group	Material	Type	Source
Rubbery Polymers	Silicone	* MEM-100	General Electric
		RTV-615	General Electric
		RTV-670	General Electric
		Silgard 184	Dow Corning
		MDX 4-4210	Dow Corning
		* Composite Silicone on Polysulfone	Membrane Technology and Research (MTR)
	Silicone - Polycarbonate	* MEM-213	General Electric
	Polyvinylidene Fluoride	Fluorel FC-2174	3M
	Nitrile Rubber	Krynac 19.65	Polysar
	Chlorosulfonated Polyethylene	Hypalon 20	DuPont
	Chloroprene	Neoprene W	DuPont
Polysulfones	Udel	P3500	Union Carbide
	Victrex		ICI
Other Polymers	* Polyimide		Northern Telecom
Selective Additives	Zeolite	S-115	Union Carbide
	Extractants	Diisopropyl-L-tartrate	Ranked #1
		1,7 - Heptanediol	Ranked #4
		2-Ethyl-1,3-hexandiol	Ranked #6
		2-Ethyl-hexanoic acid	

Notes: *Obtained as a membrane or sheet

TABLE 2

SUMMARY OF COMPATIBILITY AND SELECTIVITY OF POLYMERS TESTED

Material	Compatibility to Vapour Ethanol	Selectivity To Vapour Ethanol
Silicone	Okay	Low, declined with temperature.
Silicone-Polycarbonate	Okay	Not selective to ethanol.
Neoprene	Degraded	
Fluorel	Okay, but excessive permeability.	
Nitrile Rubber	Excessive permeability.	
Hypalon	Excessive permeability.	
Udel Polysulfone	Destroyed	
Victrex Polysulfone	Degraded	
Polyimide	Okay	Very low permeability

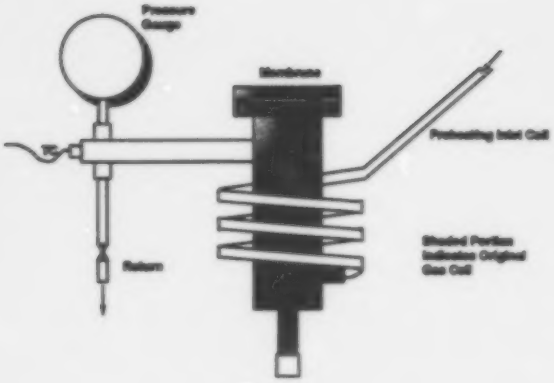


Figure 1. Small Cell Assembly (10.7 cm^2 area)

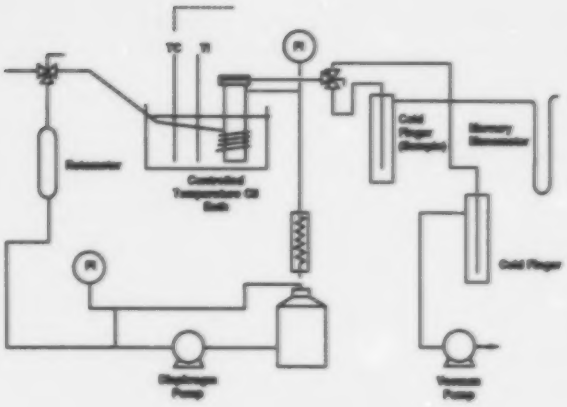


Figure 2. Small Cell System Schematic Diagram

Figure 3. Selectivity Comparison of all Silicone Films Tested
Separation Factor (α_{ew}) as a Function of Temperature for Feed near 50% Ethanol

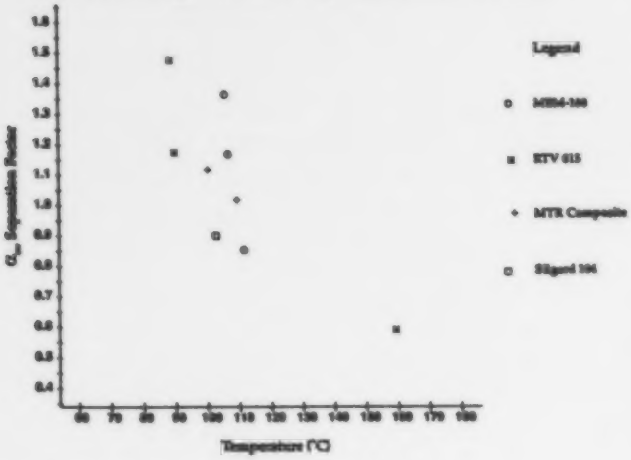


Figure 4. Selectivity of Silicone Films Incorporating S-115 Zeolite
Separation Factor (α_{ew}) as a Function of Temperature for Feed near 50% Ethanol

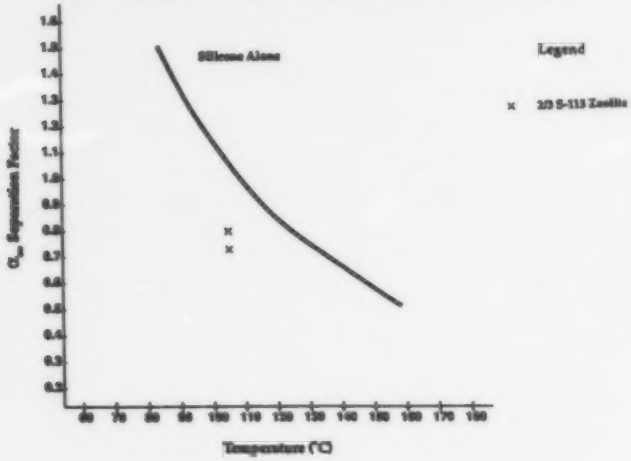
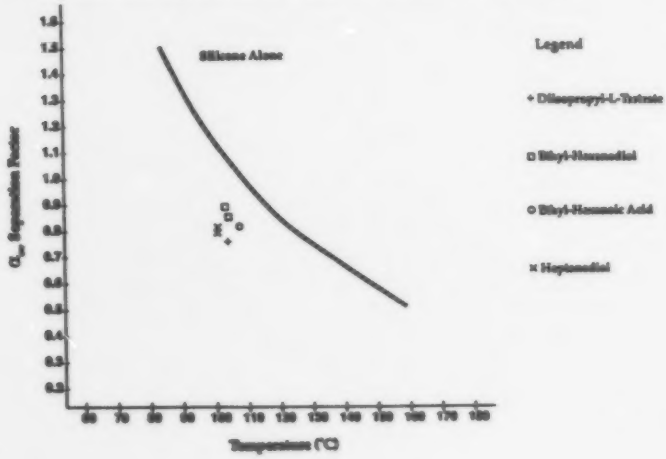


Figure 5. Selectivity of Silicone Films Incorporating Ethanol Extractants
Separation Factor (α_{ew}) as a Function of Temperature for Feed near 50% Ethanol



P3-23

DEVELOPMENT OF ETHANOL SENSOR FOR BIOFUEL FERMENTATION

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SUMMARY

The aim of the project is the development of an industrial prototype sensor for the measurement of ethanol concentrations in biofuel fermentations. The operating principle of the sensor is based on the ethanol diffusion through a selective tubular membrane into a ducted and precision controlled stream of carrier gas leading to a Taguchi #812 gas sensor. A special circuit was developed for signal generation and evaluation. The gas sensor and ducting, thermal sensor and associated circuitry are contained in a rugged, stainless steel casing, which also supports and exposes the membrane to the fermentation broth. The sensor response was maximized for low ethanol concentrations to provide industry with a reliable means of measurement for the most critical early fermentation phase. The working range extends from 0% to 15% volume at temperatures between 6 and 40° C. Sensor performance will be demonstrated with a microcomputer based control unit. A pending inquiry for patent protection or licensing will not allow disclosure of technical details about sensor principles, circuitry and software at the present time.

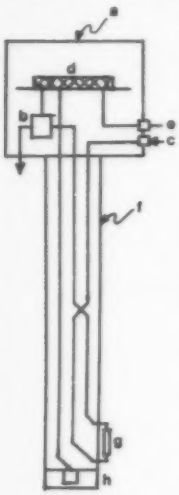
Le but de ce projet était de mettre au point un prototype de détecteur industriel qui permettrait de déterminer les concentrations d'éthanol pendant la production de biocombustibles par fermentation. Voici le principe de ce détecteur: l'éthanol diffuse à travers une membrane tubulaire sélective jusque dans un gaz porteur s'écoulant à un débit contrôlé avec précision dans un tube menant à un détecteur de gaz Taguchi n° 812. On a mis au point un circuit spécial pour produire un signal et l'évaluer. Le détecteur de gaz et ses tubes, le thermodétecteur et le circuit sont contenus dans un robuste boîtier en acier inoxydable, dans lequel se trouve la membrane qui est exposée au bouillon de fermentation. On a maximisé la réponse du détecteur pour qu'il puisse déceler de faibles concentrations d'éthanol; l'industrie disposera ainsi d'un appareil de mesure fiable utilisable au cours de la première phase de fermentation, qui est la phase la plus critique. La plage de concentrations utilisable est de 0 - 15 % à des températures comprises entre 6 et 40 °C. On évaluera le rendement du détecteur à l'aide d'une unité de contrôle à micro-ordinateur. Une enquête actuellement en cours sur la protection conférée par le brevet et les droits d'exploitation sous licence nous interdit pour le moment de divulguer des détails techniques sur les principes, les circuits ou les logiciels.

INTRODUCTION

The objective of the project was to develop a low cost ethanol sensor for the control and optimization of biofuel fermentations. A simple, but promising chromatographic principle involving a low cost, tubular silicone membrane, a Taguchi TGS #812 gas sensor and compressed medical air as a carrier gas as described by Clifford and Tuma 1983, Heiland 1982, Kempe and Schallenberger 1983 and Klopper et al 1987 was selected. The membrane is submerged into the fermentation broth to allow ethanol to diffuse trough its walls into the carrier gas, which is fed into the gas sensor. For a proper selection of flow rate, membrane size and electronic circuitry the sensor will generate an output signal, which can be calibrated to measure the ethanol concentration in the fermentation broth. Specific goals were to develop a shock and leak proof prototype with proper signal conditioning and thermal compensation for use in industrial fermentations.

RESULTS

The prototype sensor presented at the 7th Canadian Bioenergy R&D Seminar has a sealed housing (a) for the encapsuled sensor (b), carrier gas ducts (c), and circuit board (d) as shown in the schematic layout below. A sensor stem (f) with ducting and electrical conduct (e) for the thermal sensor (h) extends from the upper housing and has the external membrane (g) mounted at its lower end. The carrier gas flow rate is adjusted with a precision control valve. Both, a cylinder with compressed medical air and the flow control valve have standard industrial specifications. Extensive testing with precisely known solutions of ethanol in water were used to establish the basic formula as well as the thermal parameters of the sensor performance. The 4-20 mA output signal of the sensor is fed into a small process computer, which converts it to a volumetric concentration for display together with the fermentation temperature and other process variables. This computer was used in industrial experiments for adaptive fermentation control with a central management computer. Technical details will be released soon, when patenting and licensing issues have been cleared. Fermentation experiments with grain and corn mash continue at the present time.



DISCUSSION

Sensor hardware and associated software have been functioning with very high reliability over long periods of time in industrial trials. Also reliable performance formulas have been established for a limited number of fermentation substrates. Work continues to expand the application range. The system was successfully used in the wine industry for fermentation monitoring as well as temperature control. It is designed to be more sensitive in the critical early fermentation period immediately after inoculation. Adaptive control methods for improved system response have been developed. It is hoped, to market the system for biofuel as well as beverage fermentation control in the near future. The discussion of technical details needs to be delayed until that time due to the pending patent review.

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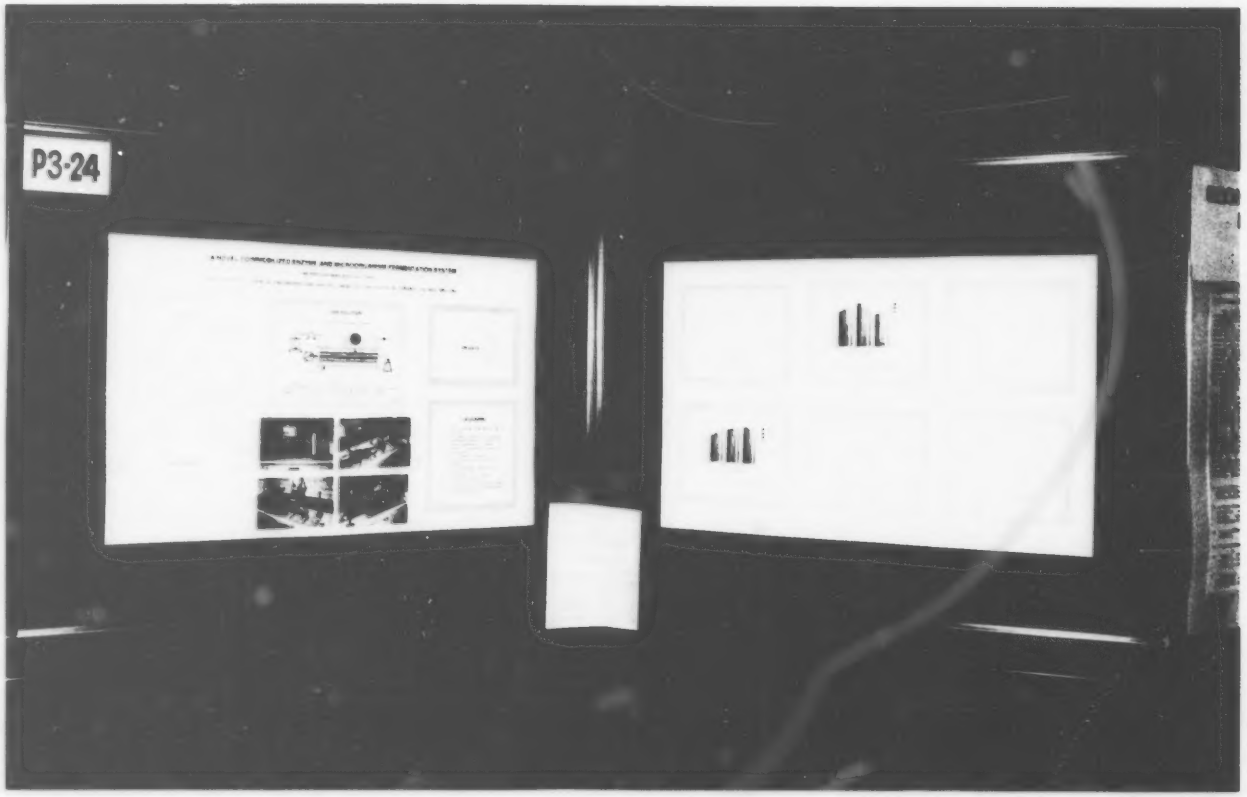
P3-24

A NOVEL COIMMOBILIZED CELLULASE ENZYME AND YEAST CONTINUOUS FERMENTATION SYSTEM

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A new simple technique to entrap bakers' yeast, Saccharomyces cerevisiae, on DuPont glass fibre sheet with alginate, followed by precipitating and crosslinking commercial cellulases, Meicelase and 1,4-B glucosidase, with tannin and glutaraldehyde, was developed. Some conditions involved in the coimmobilization reactions were investigated. The cellulase/yeast coimmobilizate was applied to simultaneous saccharification and fermentation (SSF) of delignified aspen wood. SSF with the coimmobilizate resulted in more than 87.5% efficiency in converting the aspen cellulose to ethanol within 48 hours in the first seven reuses when SSF was carried out in a batch mode, and more than 77% efficiency in the first ten days when SSF was conducted in a continuous dynamic immobilized biocatalyst bioreactor (CDIBB) with a residence time of 48 hours. The half life of the coimmobilizate was more than two weeks in both cases.

Une nouvelle technique simple d'attraper la levure, Saccharomyces cerevisiae, sur plaque DuPont en fibre de verre avec alginate, suivie de précipitation et de liaison croisée des cellulases de commerce, Meicelase et 1,4-B glucosidase, avec du tanin et du glutaraldehyde, fut développée. Quelques conditions, impliquées dans les réactions co-immobilisées, furent recherchées. La cellulase/levure co-immobilisée fut appliquée aux saccharification et de fermentation simultanées (SSF) de tremble délignifié de bois. SSF avec cellulase/levure co-immobilisée, a pour résultat plus de 87.5% d'éfficiencé en transformant le tremble cellulosique à l' ethanol en moins de 48 heures dans les septs premiers cellulase/levure re-utilisées quand le SSF fut réalisé en fournée, et plus de 77% d' éfficience dans les dix premiers jours quand SSF fut conduit dans un bio-réacteur dynamique continuel immobilisé bio-catalyseux (CDIBB) avec un temps résidentiel de 48 heures. La demie-vie de cellulase/levure coimmobilisée était plus de deux semaines dans les deux cas.

INTRODUCTION

Today's environmental concern and tomorrow's possible oil shortage require more use of ethanol as either an octane enhancer in unleaded gasoline or a gasoline substitute. Forestry waste and agriculture residues are considered cheap sources of raw materials for the production of fuel alcohol. In order to accomplish the transformation from these lignocellulosics to ethanol, the key step is to break down the cellulose fraction into its component sugar glucose, which is then fermented to ethanol. As reported by a number of investigators (1, 2, 3), enzymatic saccharification has potential for industrial application. However, the main handicap of the enzymatic approach is the high cost of cellulases. It was estimated that up to 70% of the energy demand of saccharification is in cellulase production (4). An economically competitive enzymatic process is , therefore, based on the reduction of the cost of cellulases and improvements of the over-all process.

One of the effective approaches to lower the enzyme requirement is immobilization. Immobilized cellulases have now been demonstrated to be able to catalyse the saccharification of an insoluble cellulose (5, 6, 7, 8). C. Mishra and M. Rao (5, 6) immobilized cellulases on poly vinyl alcohol using carbodiimide which catalysed the hydrolysis of alkali-treated Solka-floc and bagasse with 55-65% conversion in 24 hours. M.B. Fadda et al (7) reported the ability of insoluble immobilized cellulases to saccharify natural substrates such as alfalfa, wheat straw and pine needles. They showed that the immobilized cellulases were even more efficient than the free enzymes and could be reused five cycles before reaching their half life. Albert Garcia III et al (8) studied the attachment of cellulases to iron oxide particles, resulting in 128% of the retained enzymatic activity and 272 h half life.

The yield and the rate of conversion of cellulosics to ethanol could be greatly improved by simultaneous saccharification and fermentation (SSF) (9, 10, 11); 384 L ethanol/tonne of aspen wood were obtained within 48 hours by SSF with cellulases and the mixed culture of B. clausenii and P. stipitis R compared to 346 L/tonne in 72 to 96 hours by separate saccharification and fermentation (11). In addition, advantages of the SSF also include less equipment involved, less end-product inhibition and less enzyme required.

A better option, the combination of immobilization and SSF--coimmobilization of cellulolytic enzymes and fermentative microorganisms has recently also been investigated. Barbel Hagerdal et al (12, 13, 14) coimmobilized B-Glucosidase with bakers' yeast Saccharomyces cerevisiae in alginate gel which was used in directly converting cellobiose to ethanol. It was shown that the coimmobilized biocatalysts were much better (80% compared to 40%) than the separately immobilized ones, in terms of the efficiency of converting cellobiose to ethanol, when they were applied in a packed bed reactor for two weeks (14). The same biocatalysts and similar coimmobilization method were also studied by M. Kierstan et al for the production of ethanol from cellobiose (15). A different approach, coimmobilization of bakers' yeast with cellulases by tannin and glutaradehyde was developed by W. Hartmeier (16). In his study, the yeast/cellulase coimmobilizate was also used in a packed bed reactor and could theoretically convert cellobiose or saccharified filter paper into ethanol although its long term application failed to be maintained.

In short, the reported enzyme-cell coimmobilizate could directly convert soluble cellobiose or cellodextrin to ethanol, augmenting the advantages of either immobilization or SSF alone. If a proper technique and a suitable bioreactor system could be devised in such a way that not only commercial soluble substrate but also natural insoluble cellulosics could be directly converted to ethanol with coimmobilized biocatalysts, our final goal, to produce cheaper ethanol from cellulosics, would be closer. The objectives of present investigation, therefore, are to establish techniques of coimmobilizing commercial cellulases with bakers' yeast onto DuPont glass fibre discs and to evaluate the performance of the coimmobilizate during SSF of insoluble pretreated aspen wood, in both shake flasks and in a continuous dynamic immobilized biocatalyst bioreactor (CDIBB) which is principally

similar to that which we used for high solids fermentation of hydrolysates of wheat starch B (17, 18).

DESCRIPTION OF THE COIMMOBILIZED ENZYME AND YEAST SYSTEM

In order to keep the simplicity and gentleness of gel entrapment for cell immobilization and to eliminate steric hindrance between the immobilized enzyme and insoluble substrate, the following coimmobilized enzyme and yeast system (Figure 1) was designed in the present study. The yeast C was first attached to the support A in the form of a thin layer by entrapment with sodium alginate and calcium chloride B, and then the cellulase enzymes D were linked on the surface of the cells with tannin and glutaraldehyde. The glucose resulting from the saccharification of the cellulosic substrate by the bound enzymes was converted into ethanol by the yeast entrapped in the polymer matrix as soon as it was produced.

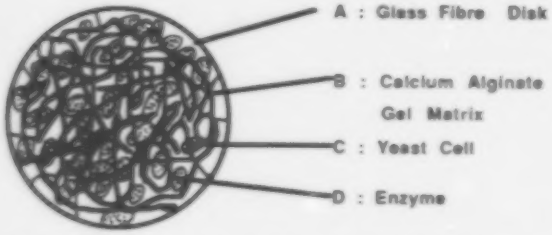

Figure 1 Coimmobilized Enzyme and Yeast System

MATERIALS AND METHODS

Materials: DuPont fibre glass was the gift of Manville EMI (Denver, Colorado, USA) ; cellulases, Meicelase, containing 28.75% of crude protein, were donated by Meiji Seika Kaisha, Ltd. (Tokyo, Japan) ; cellobiase, Novozym, containing 14.12% of crude protein, was purchased from Novo Industri, A/S (Copenhagen, Denmark). Pretreated aspen wood was obtained by passing aspen chips containing 2.6 % SO2 on wood through a Wenger reactor at 200 C and a residence time of 45 seconds as described elsewhere (19) . Delignified aspen wood was produced by cooking SO2-Wenger pretreated aspen wood in stainless steel digesters with 4% NaOH solution at 190 C for 2.5 hr. Saccharomyces cerevisiae (Fleischmann) was obtained from a local market. All other chemicals were of reagent grade.

Bioreactor: The experimental apparatus used for continous production of ethanol by SSF of pretreated aspen wood with coimmobolized biocatalysts is diagrammatically illustrated in Figure 2. The reactor was a Lucite pipe (5cm in diameter, 40cm in length) in which glass fibre discs (4.8 cm in diameter, 150 pieces) were mounted on a central stainless shaft (0.635cm in diameter) and were rotated by an adjustable speed motor. The temperature was controlled by the circulation of hot water through a Lucite water jacket (10cm in diameter). The substrate slurry was pumped into the reactor with a peristaltic pump or dropped into the reactor by gravity. There were five openings on the top of the reactor which were connected to condensers and used for the evolution of CO2. The total volume of the reactor is 800 ml; the operative volume is 600 ml.

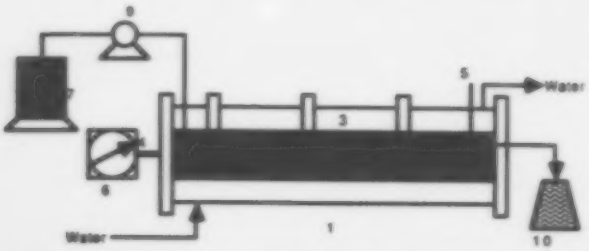

Figure 2 Schematic diagram of experimental apparatus. 1. Continuous Dynamic Immobilized Biocatalyst Bioreactor (CDIBB); 2. Glass fibre discs; 3. Heat exchange chamber; 4. Central shaft; 5. Thermometer; 6. Motor; 7. Substrate reservoir; 8. Magnetic stirrer; 9. Peristaltic pump; 10. Product reservoir.

Entrapment of Yeast on DuPont Glass Fibre Support: For shake flask studies, 7.0 g of bakers yeast was added to 25 mL of sterilized saline containing 10g/L glucose in a 50 mL flask, and 0.16 g to 0.48 g alginate was added. The mixture was stirred for 15 min. 2.0 g sterilized DuPont glass fibre support was then placed into the flask which was shaken on a rotary shaker at 150 rpm, room temperature for 20 min. Excessive yeast slurry was drained and stored for future use. Then 20 mL of 4% CaCl2 solution containing 0.1 g/L DAP and 0.2 g/L urea was added. The reaction continued at room temperature, 120 rpm, under anaerobic conditions for 8 hours. At the end of that time, the cells supports were washed with sterilized saline to remove free cells. For using the CDIBB, the bioreactor loaded with DuPont glass fibre discs and the tubings were sterilized with 5% formaldehyde solution and then washed with hot sterile water. 300 mL of the above cell slurry containing 1% sodium alginate was introduced into the reactor; the fibre discs were rotated by the motor at room temperature for four hours to obtain uniform coating of the cell slurry onto the disc surfaces. Excessive cell slurry was then decanted and 300 mL of the CaCl2 solution was added to harden the alginate gel matrix. The remaining procedures for cell immobilization were the same as those used in the shake flask studies.

Precipitation of Cellulases on Immobilized Yeast: 10 ml of 2.95 % to 11.8 % (based on protein content) cellulase solution (Meicelase : B-glucosidase = 3:1, protein basis) was shaken with the above immobilized yeast at 120 rpm, room temperature for 20 min. The supernatant was decanted and kept for reuse ; the support bearing cells and enzymes was allowed to react with 10 mL of 1% - 3% tannin and 0.2 mL of 10 % glutaraldehyde at room temperature with constant shaking at 100 rpm for 4 hours. At the termination of the reaction, the coimmobilizate was washed with sterilized saline followed by 0.01 M acetate buffer ten times to remove free enzymes and cells. The resulting coimmobilizate was directly used for SSF. For the CDIBB runs, 300 mL of 9.95% cellulase solution and 300 mL of 1% tannin solution were used for the crosslinking reaction. About the same volume of the cellulase solution was decanted from the reactor after adsorption by the entrapped cells and kept for reuse. The other steps were as described above.

SSF of Pretreated Aspen Wood with the Coimmobilizate: The resulting coimmobilizate was used to simultaneously saccharify and ferment 10 mL of 8.13 to 10.61 g/L delignified aspen wood containing 90.48% cellulose, 9.52 % lignin and others (on dry basis), 0.1 g/L DAP and 0.2 g/L urea. SSF was conducted at pH 4.8, 37 C and 120 rpm (12 rpm for CDIBB) anaerobically for 48 hours. At the end of SSF carried out in shake flasks , the ethanol solution was separated ; the coimmobilizate was reused for the SSF of fresh substrate. This procedure was carried out for 10 to 16 days. When SSF was conducted in the CDIBB, the ethanol solution was continuously drained out at the end of the reactor at a flow rate of 0.21 mL/min, corresponding to a residence time of 48 hours.

Analysis: Glucose was analysed by HPLC (Sugar Analyser 1, Waters) with an Aminex HPX - 87P column at 65 C, using water as eluent, Refractive Index detector and 16 g/L n-propanol as the internal standard (20).

Ethanol was determined by GC (5700A, Hewlett Packard) with an ion flame detector, using 7.0 g/L n-propanol as the internal standard (21).

Protein content was obtained by measurement of nitrogen with the standard method of Kjeldahl.

RESULTS AND DISCUSSION

Effect of Concentration of Tannic Acid: Tannins are polyphenolic compounds and named from their tanning action on proteins. The

principal constituent of the commercially available tannin is tannic acid or gallotannic acid. Because of their capability of binding strongly to protein, tannins have not only been adopted in leather manufacture for centuries but also have been used for precipitating cellulases to recover them (22) or to immobilize them (23). The binding ability to protein of tannins, on the other hand, could inhibit a variety of enzymes include cellulolytic enzymes (24, 25) and microbial cells (26). It should be realized from these facts that the amount of tannin applied in immobilization under certain conditions could be very critical. Therefore, the concentrations of tannic acid used for precipitating cellulases on yeast surfaces under the described conditions were studied (Figure 3).

Three different levels, 1%, 2% and 3%, of tannin solution were examined. Ethanol yield of SSF of delignified aspen wood with coimmobilizates was chosen as a criteron and was also used in the other experiments to determine optimal conditions. It was found that the activity of the coimmobilized biocatalysts was completely lost after two repeated uses for SSF when 3% of tannin solution was used. The higher initial activity of the coimmobilizate with 3% tannin could have resulted from over- saturation of severely denatured cellulases on yeast surfaces which could easily be detached from the cell surfaces during SSF, no sugar being detected. But such a serious denaturation effect on cellulases was not encountered when the concentration of tannin solution was lower than 2%. There was no significant difference in ethanol yield between 1% and 2% tannin until the fourth reuse of the coimmobilizates. However, after eight days of SSF, the activity of the coimmobilizate prepared from 1% tannin declined quickly during the following two reuses while the decrease was observed six days later in the case of 2% tannin. The faster decline in activity with 1% tannin could mainly have resulted from the leakage of cellulases from the yeast owing to the loose binding. A tannin concentration of 2% was , therefore, considered to be fairly optimal and was used in the following experiments.

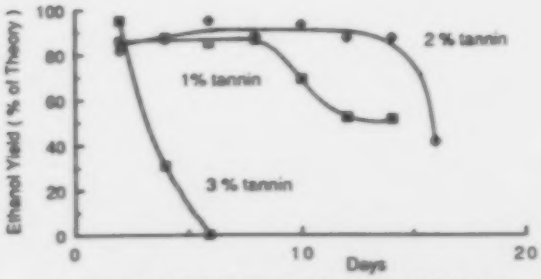

Figure 3 Effect of Concentration of Tannin Solution on Ethanol Yield during SSF of Pretreated Aspen Wood with Coimmobilized Cellulase and Yeast

Effect of Concentration of Alginate Solution: Cells trapped in open alginate gel matrix in the present study served the function not only of biocatalysts but also as intermediate binding layers between support and enzymes. In other words, cells should, on one hand, be firmly entrapped on the support surface by a three-dimentional gel matrix, on the other hand, still have free surface available for binding cellulases. The concentration of alginate in the cell slurry before immobilization can be reflected in the porous structure of the immobilized cell composites. Therefore, the effect of the concentration of alginate on the resulting coimmobilizate was examined.

Figure 4 and Figure 5 show the relationship between concentration of alginate used for coimmobilization and ethanol yield obtained with the coimmobilizate during SSF of the pretreated aspen wood. The ethanol yield varied with the concentration of alginate, but the variation also depended on the enzyme concentration as well as the number of times of repeated use of the coimmobilizate. When a higher concentration of cellulase solution was employed (Figure 4), the ethanol yield increased by about 20% with the increase of the concentration of alginate from 0.5% to 1.0% in the first two reuses of the coimmobilizate, but the yield increased much less with further increase of the concentration of alginate. In addition, the increase in the yield was much less significant in the third and the fourth reuses with the increase of alginate concentration. On the other hand, Figure 5 demonstrates that when a lower concentration of enzyme solution was used, maximum conversion of cellulose to ethanol was achieved with 1.0% alginate in the first reuse; however, there was a decrease in conversion with increase of alginate concentration in the following reuses. The optimal concentrations of alginate that led to the maximum ethanol yield were 1.5% for 11.8% cellulase solution and 0.5% for 5.9% cellulase solution.

The above effects may have resulted from a combination of the factors such as gel strength, growth rate of cells, diffusivities of the substrate, effective surface for enzyme binding, tannin inhibition and adsorption of enzyme by alginate gel. As the concentration of alginate in the binding layer increases so will the mechanical strength of the fixed cell mass but the growth of cells will decrease, which should be minimized to avoid disrupting the matrix with resulting cell leakage. Increasing alginate concentration will also decrease effective cell surfaces for binding cellulases, diffusivities of the substrate and tannin attack on cells. Alginate gel itself may adsorb enzymes although it was reported not to retain proteins such as γ-globulin and bovine serum albumin (27).

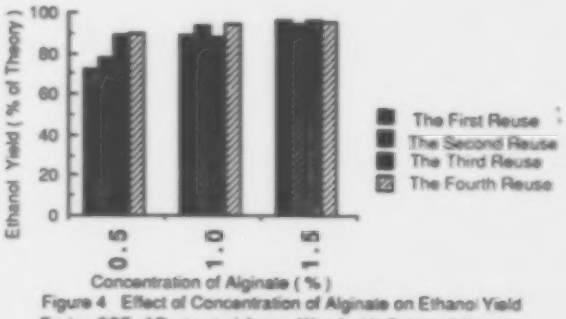

Figure 4 Effect of Concentration of Alginate on Ethanol Yield During SSF of Pretreated Aspen Wood with Coimmobilized Cellulase and Yeast. Cellulase Concentration : 11.8 %. Shake Flask Runs.

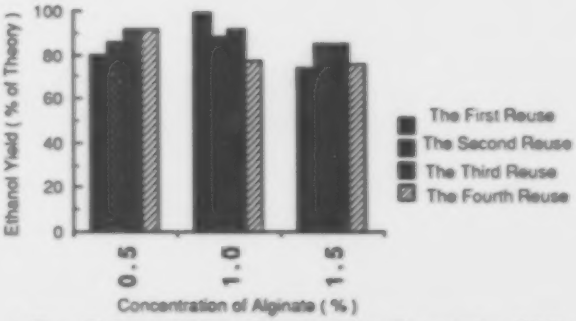

Figure 5 Same as Figure 4 Except Cellulase Concentration : 5.9 %

Effect of Concentration of Enzyme Solution: Cellulase concentration was the limiting factor for SSF of cellulose. High productivity of ethanol depended on sufficient loading of cellulase on the cell surfaces, while the degree of enzyme saturation on the surfaces was determined by the concentration of the enzyme solution used for immobilization. Studies with varied concentration of cellulase solution under a fixed

concentration of alginate were, therefore, also conducted. The relationship between the concentration of cellulase solution and percentage of conversion of cellulose to ethanol by the coimmobilizate is shown in Figure 6 and Table 1. It was found that the yeast/cellulase coimmobilizate performed best during five successive runs of SSF of aspen cellulose when it was prepared with a cellulase concentration of 5.9% when 0.5% alginate was used; the efficiency of SSF with the coimmobilizate, however, increased from 60.0 % to 87.1% and from 74.6% to 88.1% with increase of concentration of enzyme solution from 2.95% to 11.8% and from 5.9% to 11.8% when 1.0% alginate and 1.5% alginate were employed respectively. It is evident that the effect of concentration of cellulase solution was associated with the structure of the alginate gel and the status of the cells in the gel matrix. Higher concentrations of the cellulase solution could lead to higher loading of enzyme on the surface of the cells or even on the gel matrix, but may inhibit the viability of the cells. Furthermore, the additional protein may be only physically adsorbed or aggregated on the cell surfaces or gel matrix and easily detached, if a higher concentration of cellulase solution is used.

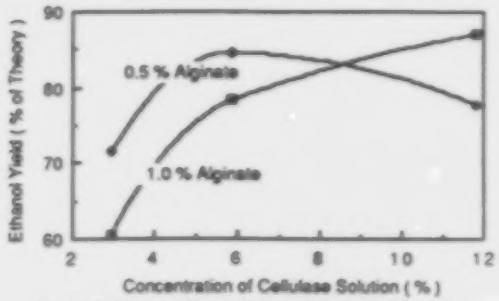

Figure 6 Effect of Concentration of Cellulase Solution on Ethanol Yield During SSF of Pretreated Aspen Wood with Coimmobilized Cellulase and Yeast. Shake Flask Runs.

Effect of Glutaraldehyde: Glutaraldehyde can be used to crosslink enzymes previously coupled on the surface of yeast to form a monolayer of immobilized enzymes, or to cause crosslinking between enzymes and cells under relatively mild conditions so that higher stability of the coimmobilized enzyme could be expected. However, glutaraldehyde can not only denature the enzymes but also decrease the viability of yeast. We did not determine the optimal usage of glutaraldehyde. We found, however, glutaraldehyde resulted in a long lag time of SSF, but an increase in the stability of the coimmobilizate (Figure 7). Considering the overall conversion of aspen cellulose to ethanol in five repeated uses (Table 1), the coimmobilizate treated with glutaraldehyde gave better results than that without the glutaraldehyde treatment.

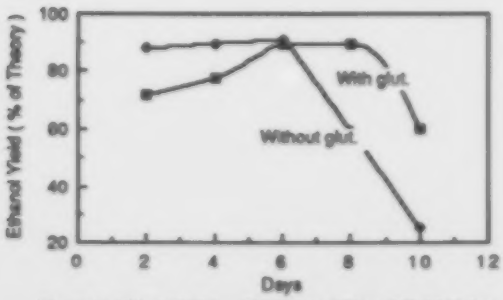

Figure 7 Effect of Glutaraldehyde on Ethanol Yield during SSF of Pretreated Aspen Wood with Coimmobilized Cellulase and Yeast. Shake Flask Runs.

TABLE 1 Results of SSF of Delignified Aspen Wood with Coimmobilized Yeast and Cellulase on DuPont Glass Fibre Support. Shake Flask Runs.

Test No.	Addition of glut.	Conc.of alginate (%)	Conc.of enzyme (% of protein)	Average of 5 repeated uses	
				Ethanol (g/L)	% of theory
1	Yes	0.5	11.8	4.15	77.8
2	Yes	1.0	11.8	4.65	87.1
3	Yes	1.5	11.8	4.71	88.1
4	Yes	0.5	5.90	4.53	84.7
5	Yes	1.0	5.90	4.19	78.4
6	Yes	1.5	5.90	3.99	74.6
7	Yes	0.5	2.95	3.82	71.5
8	Yes	1.0	2.95	3.24	60.6
9	No	0.5	11.8	3.78	70.8

2.0 g (1 cm x 2cm sheet) support; 10 mL of 10.39 g/L delignified aspen wood as substrate; SSF time: 48 hours for each use.

Operational Stability of the Yeast/Cellulase Coimmobilizate: The operational stability of the coimmobilizate was examined by its repeated use for SSF of delignified aspen wood in shake flasks or by its application in the CDIBB. Typical results illustrating the operational stability of the coimmobilizate are shown in Figure 3 (line 2), Figure 8 and Table 2.

When SSF of 8.2g/L of delignified aspen wood by the coimmobilizate was carried out with repeated batchwise operations, about 87.5% conversion of aspen cellulose to ethanol in the first seven reuses was achieved. When SSF of 10.67 g/l of the aspen wood by the coimmobilizate was conducted in the continuous bioreactor with a constant flow rate of 0.21 ml/min, corresponding to a residence time of 48 hours, around 91% of the conversion of theory in the first five days and 61% in the following week were obtained. The half life in both cases was more than two weeks. There was no contamination observed during the prolonged operation.

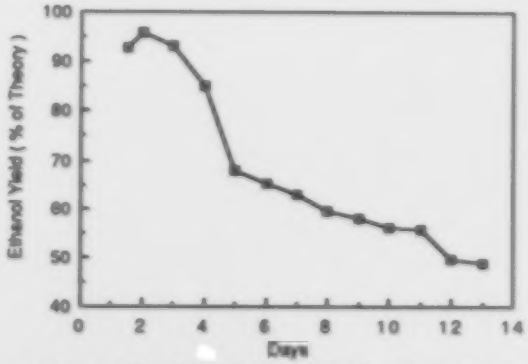

Figure 8 SSF of Delignified Aspen Wood by Coimmobilized Yeast and Cellulase in the CDIBB

TABLE 2 SSF of Delignified Aspen Wood by Coimmobilized Yeast and Cellulase.

OPERATION MODE	CONC.OF SUBSTRATE (g/L)	TIME OF SSF (h)	ETHANOL (AVERAGE) (g/L)	(%)of THEORY	HALF LIFE (days)
FLASK	8.20	48	3.42	81.9	16
CDIBB	10.67	48	3.82	70.1	14

CONCLUSIONS

The results demonstrated that the enzyme and the yeast coimmobilized by the present technique can be used for efficient SSF of insoluble pretreated aspen wood over a fairly long period. There have been no data available on SSF of natural cellulosics with coimmobilized enzymes and cells, but the results given in the present paper are better than those reported in the literature dealing with glucose production from cellulosics by immobilized cellulases. The loss of activity of the biocatalysts during prolonged operation in the present study was higher than that of other kinds of immobilized enzymes which catalyze water soluble substrates. The loss may be caused by : 1) abrasion of enzymes from the cell surfaces and leakage of cells from the support during the constant rubbing between the coimmobilizate attached to the support and the solid substrate; 2) denaturation of the cellulases during SSF; 3) abrasion of support and 4) accumulation of lignin after SSF of the pretreated aspen wood which was delignified but still not lignin-free, resulting in strong bonding between lignin and immobilized enzyme. The stability, however, can be improved by the precise balance of the multifactors.

The technique of coimmobilization of commercial cellulases and bakers' yeasts was established by entrapping cells on glass fibre discs with alginate gel matrix, followed by precipitating cellulases onto the cell surfaces. The coimmobilizate was adopted for effective SSF of insoluble cellulosics in CDIBB. The technique developed in the present study involved simple procedures and cheap chemicals (alginate and tannin). The reactor system established was also simple to design and easy to operate and could play dual functional roles. The results suggest that the present coimmobilization system could not only make this process more productive but also save the expensive biocatalysts in the production of other fermentation products and open up other opportunities in the fermentation and food industries.

ACKNOWLEDGEMENTS

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ECONOMIC AND PROCESS OPTIMIZATION OF ETHANOL PRODUCTION BY EXTRACTIVE FERMENTATION

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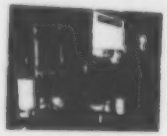

P3-25

ECONOMIC AND PROCESS OPTIMIZATION OF ETHANOL PRODUCTION BY EXTRACTIVE FERMENTATION

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The technical and economic feasibility of extractive fermentation as an alternative to conventional industrial ethanol fermentation is being examined. The optimum economic operating conditions for the extractive fermentation system developed at Queen's University are being determined by computer simulation. These conditions will be tested on a previously operated process demonstration unit which is being modified with upgraded and more sophisticated equipment components. These operating conditions will be compared to the industrial-scale operation of a conventional continuous stirred tank fermentation process with cell recycle, and the economic practicability of retrofitting an existing facility with an extractive fermentation system is being studied. Sensitivity analyses involving conventional and extractive fermentation processes will be undertaken.

On étudie dans quelle mesure il serait faisable, au point de vue technique et économique, de remplacer la méthode classique de production industrielle de l'éthanol par fermentation, par une méthode de fermentation extractive. Les conditions de fonctionnement économique optimales pour le système de fermentation extractive mis au point à l'Université Queen's sont en train d'être déterminées par simulation par ordinateur. Ces conditions seront testées au moyen d'une unité de démonstration du procédé ayant déjà été utilisée et que l'on modifie actuellement pour l'améliorer et y ajouter des éléments d'équipement plus perfectionnés. Ces conditions de fonctionnement seront comparées à l'application, à l'échelle industrielle, du procédé de fermentation classique en réservoir avec agitation continue et recyclage des cellules. On étudie actuellement dans quelle mesure il serait pratique d'équiper une installation existante d'un système de fermentation extractive. On entreprendra des analyses de sensibilité portant sur la methode classique de fermentation et sur la méthode de fermentation extractive.

INTRODUCTION

Perhaps the most distinguishing feature of the production of ethanol by fermentation is the phenomenon known as end product inhibition, which manifests itself as a significant reduction in reaction rate as the ethanol product accumulates in the fermentation broth. The practical and economic implications of this are a limit on the concentration of fermentable sugars which an organism can completely convert (≈ 18-20% w/v), and a concomitantly large amount of water which must be processed. By extracting the ethanol directly from a fermentation vessel through the use of an appropriate water-immiscible organic solvent, it is possible not only to significantly reduce the inhibitory effects of ethanol (thus keeping reaction rates high and allowing the complete conversion of concentrated feeds) but also to facilitate product recovery by flashing essentially pure ethanol from the extracting solvent. Such a process can be either optimally designed as a new facility, or readily retrofitted to existing plants, and has gone through several steps of development (Kollerup and Daugulis, 1985; Kollerup and Daugulis, 1986; Kollerup and Daugulis, 1987; Daugulis, et al., 1987).

In previous work (Daugulis, et al., 1987), a process demonstration unit which used a 5.5 L continuous stirred-tank fermentor was operated for over 300 hours under extractive fermentation conditions. This experiment confirmed the thermal and chemical stability of the solvent, which is comprised mostly of oleyl alcohol, during extended continuous operation. As well, the ethanol productivities, based on ethanol recovery from the solvent stream, that could be achieved by extractive fermentation were determined, and high concentrations (≈ 70% by weight) of ethanol were produced without distillation.

The current work involves extensive computer simulation to identify the optimum economic operating conditions of an extractive fermentation system, and to determine the economic feasibility of extractive fermentation on a plant scale relative to conventional ethanol technology. The optimum operating conditions, along with sensitivity analyses, will be tested on an upgraded version of the previously operated process demonstration unit.

METHODOLOGY

Computer Simulation

Software was written to simulate the operation of a continuous stirred-tank fermentor with cell recycle under conventional and extractive fermentation conditions. The program was used to determine the effects of cell recycle on an extractive fermentation system. The program was translated into Fortran© and incorporated into Process™, a commercially available simulation software package. This provided Process™ with a new module which would allow it to simulate any flowsheet which incorporated a bioreactor, and would thus allow it to simulate an extractive fermentation process as well as conventional fermentation technology for the purpose of economic modelling.

Economic Modelling

To determine the relative economic competitiveness of producing ethanol by extractive fermentation, two process flow diagrams were simulated using Process™ and compared using conventional chemical engineering financial analysis. Figure I represents an ethanol plant which uses conventional technology (Maiorella, et al., 1983), while the flowsheet shown in Figure II represents a plant which uses extractive fermentation technology (Kollerup, 1986). The steady state operation of both processes was simulated over a wide range of operating conditions for a plant capacity of 100 million L/y of azeotropic ethanol, and common assumptions involving equipment costing, utilities, labour, and accounting procedures were used to provide a direct comparison of the two competing technologies on the same basis.

Improvements in PDU

Several improvements were made in the previously operated process demonstration unit, the flowsheet for which is shown in Figure III. The key design elements of the PDU were selected to reflect, as accurately as possible, the features of the full-scale flowsheet. A continuous centrifuge was incorporated to both separate the aqueous phase and cells from the solvent phase prior to vacuum flashing, and to concentrate the cells for cell recycle. The vacuum flash separator was redesigned in stainless steel to incorporate level, pressure, and temperature sensors, and to withstand high vacuum. The 10 L vessel was also equipped with sight glasses for visual observation of the solvent level within the vessel. A more effective condenser was also installed to increase ethanol recovery, and a number of diaphragm pumps were installed for solvent recycle in the fermentor, solvent withdrawal from the fermentor, and cell return from the centrifuge.

Process Control

A computer-operated process control system using CIM-PAC© software was incorporated into the process demonstration unit. This system allows individual on-off control of all pumps, and emergency shut-off control of the centrifuge motor, as well as continuous data-logging of tank levels, fermentor temperature, pressure, and pH, vacuum flash temperature and pressure, and flow indication in several solvent lines. CIM-PAC© allows the real-time display of these parameters superimposed over a computer-generated process flowsheet. As well, the system allows for manual control over the pumps for start-up.

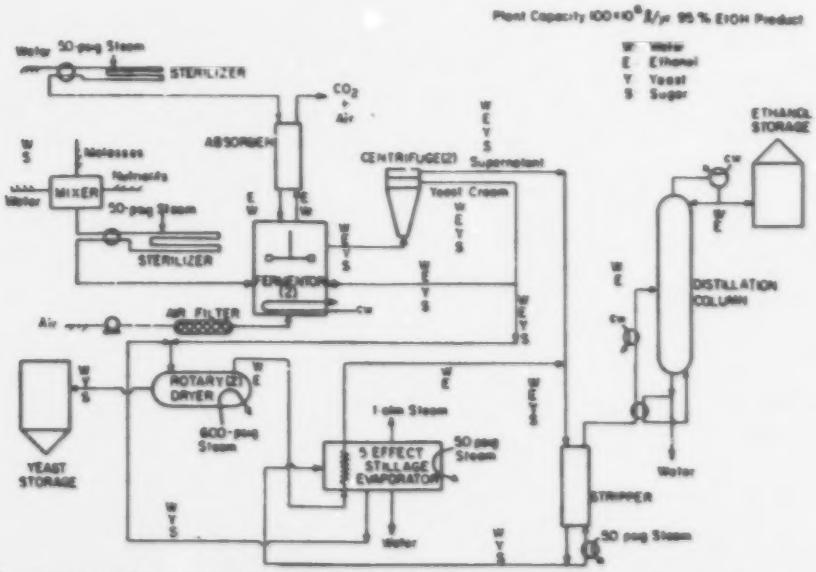

FIGURE 1: Process flow diagram for a conventional ethanol plant with cell recycle.

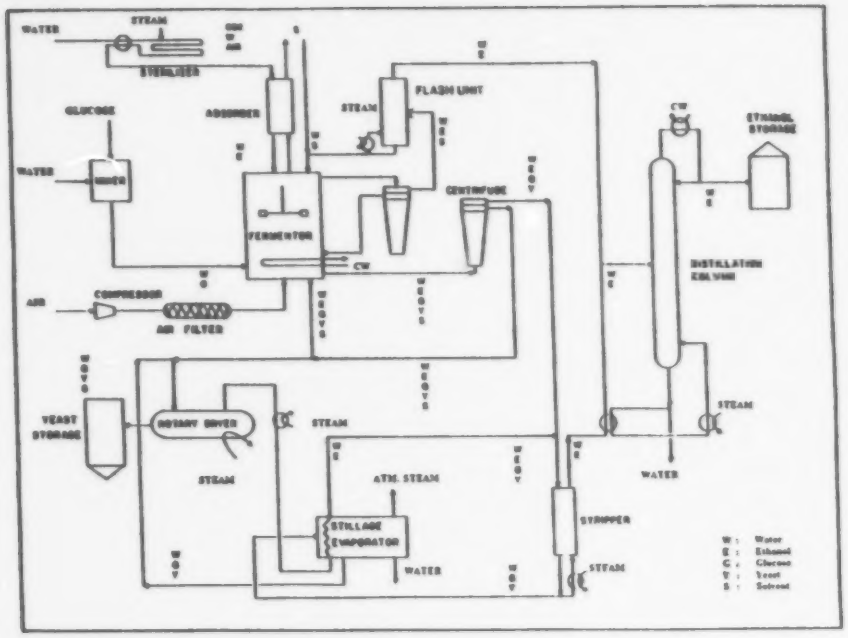

FIGURE 2: Process flow diagram for an extractive fermentation plant with cell recycle.

RESULTS AND DISCUSSION

It was confirmed from computer simulation that cell recycle would result both in higher ethanol productivities and greater substrate conversion for a given dilution rate. An example of this is given in Figure IV, which compares total ethanol productivities for three strategies - conventional fermentation, extractive fermentation, and extractive fermentation with cell recycle. Dilution rate is a normalized measure of throughput and is defined as the volumetric flowrate of the aqueous medium into the fermentor divided by the aqueous volume in the fermentor. For this simulation, a feed concentration of 200 g/L fermentables was chosen for the conventional process. However, an extractive fermentation process is capable of utilizing concentrated feeds (Daugulis, et al., 1987), and it is through the use of such feeds that the kinetic and economic advantages of extractive fermentation are realized. Thus, for the extractive fermentation simulations, a feed concentration of 400 g/L fermentables was used. For the cell recycle simulations, a recycle ratio of 0.15 and a cell concentration factor of 2 were used.

Evaluating the economic competitiveness of an ethanol processing strategy in absolute terms is both extremely difficult and of limited long-term value. It is difficult because of the very large number of technical and financial inputs which must be arbitrarily selected; these include such factors as capacity, plant component design, location, substrate, materials costs and credits, etc. It is of limited long-term value because of the volatility of commodity and energy prices, and the vagaries of government subsidy policies. The relative competitiveness of competing processing strategies can be extremely useful, however, as long as identical assumptions are made; any subsequent variabilities would tend to affect the alternatives to more or less the same extent, and the relative economic positions would likely remain unchanged.

For an assumed plant capacity of 100 million litres of azeotropic ethanol per year, an assumed 15% return on investment, and a very conservative engineering plant design, conventional ethanol technology was found to yield a selling price of 47 ¢/L in 1989 Canadian dollars at the optimal operating conditions of the plant. This outcome is obviously contingent upon all of the enormous number of technical and financial assumptions which went into the simulation, and would change as the assumptions changed. Under identical financial conditions and at its optimum, the extractive fermentation process gave an ethanol selling price of 40 ¢/L, a saving of 7 ¢/L, or an increase in revenue of 7 million dollars per year. Retrofitting an existing conventional plant to operate as an extractive fermentation process appears to be an even more economically attractive option. We are currently examining considerations such as pay-back period and the effect of increased production capacity and reduced energy consumption under various retrofit scenarios. It is felt that all of the mathematical models, assumptions, and process simulations in the present analysis could readily withstand close scrutiny, and that the economic attractiveness of extractive fermentation has now been clearly demonstrated.

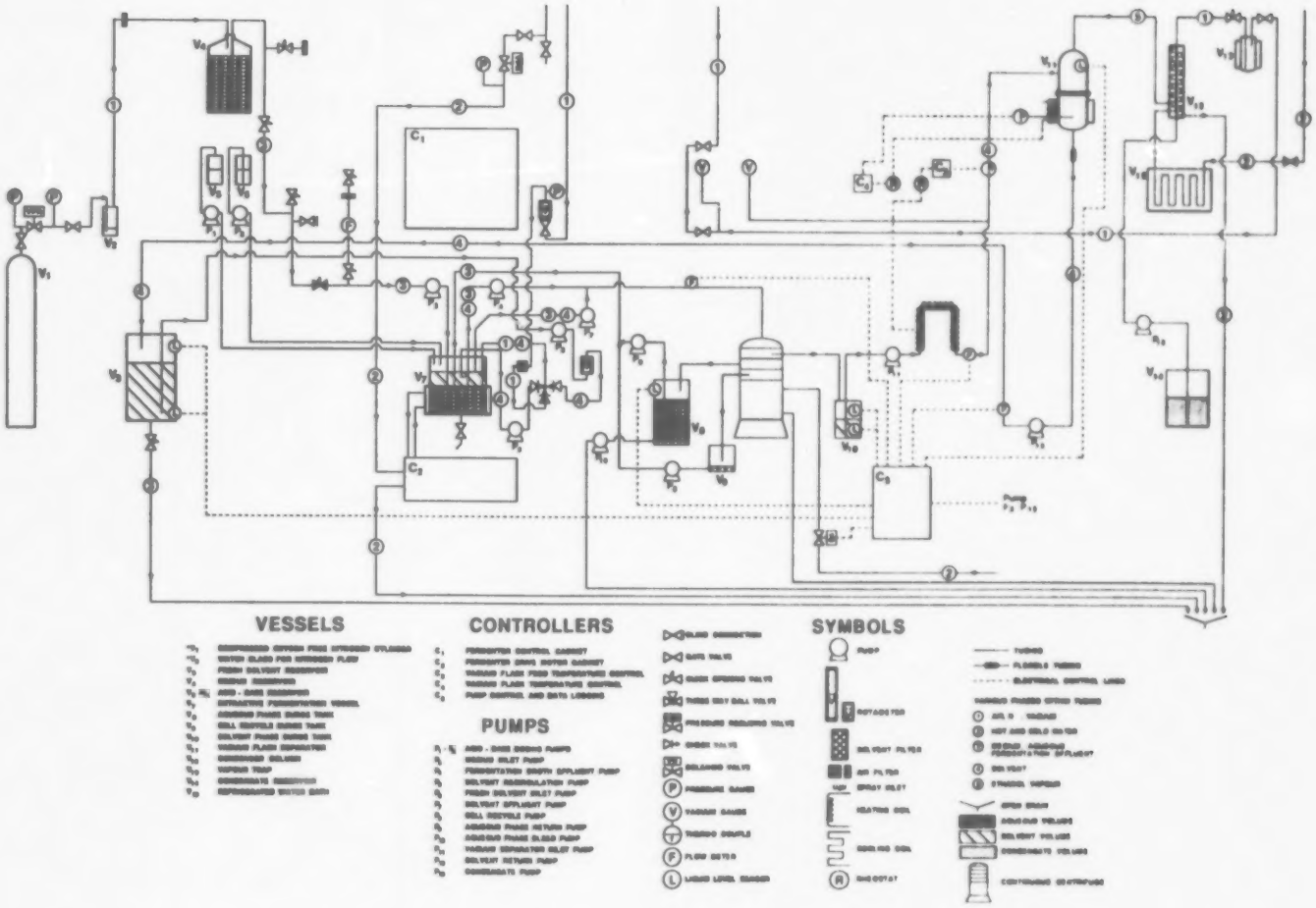

FIGURE III: Flow diagram for extractive fermentation process demonstration unit.

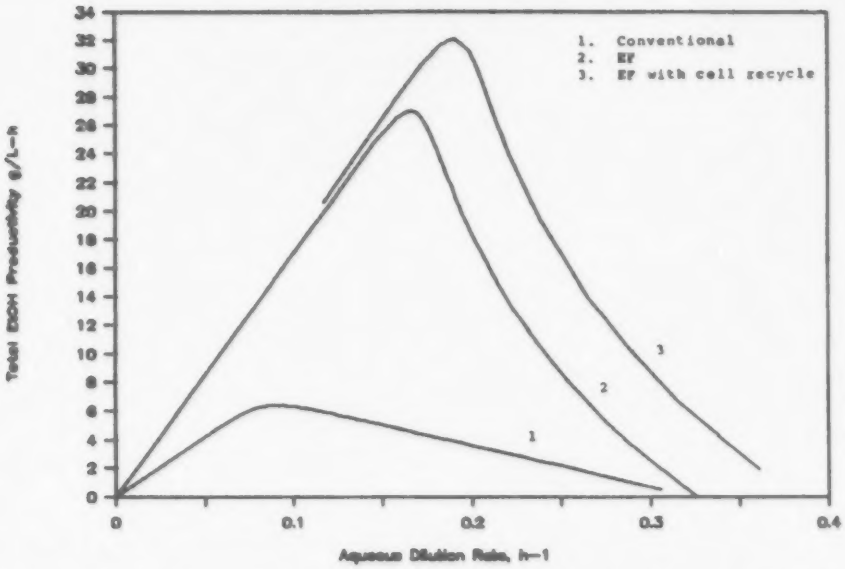

FIGURE IV: Total ethanol productivities using conventional fermentation, extractive fermentation, and extractive fermentation with cell recycle.

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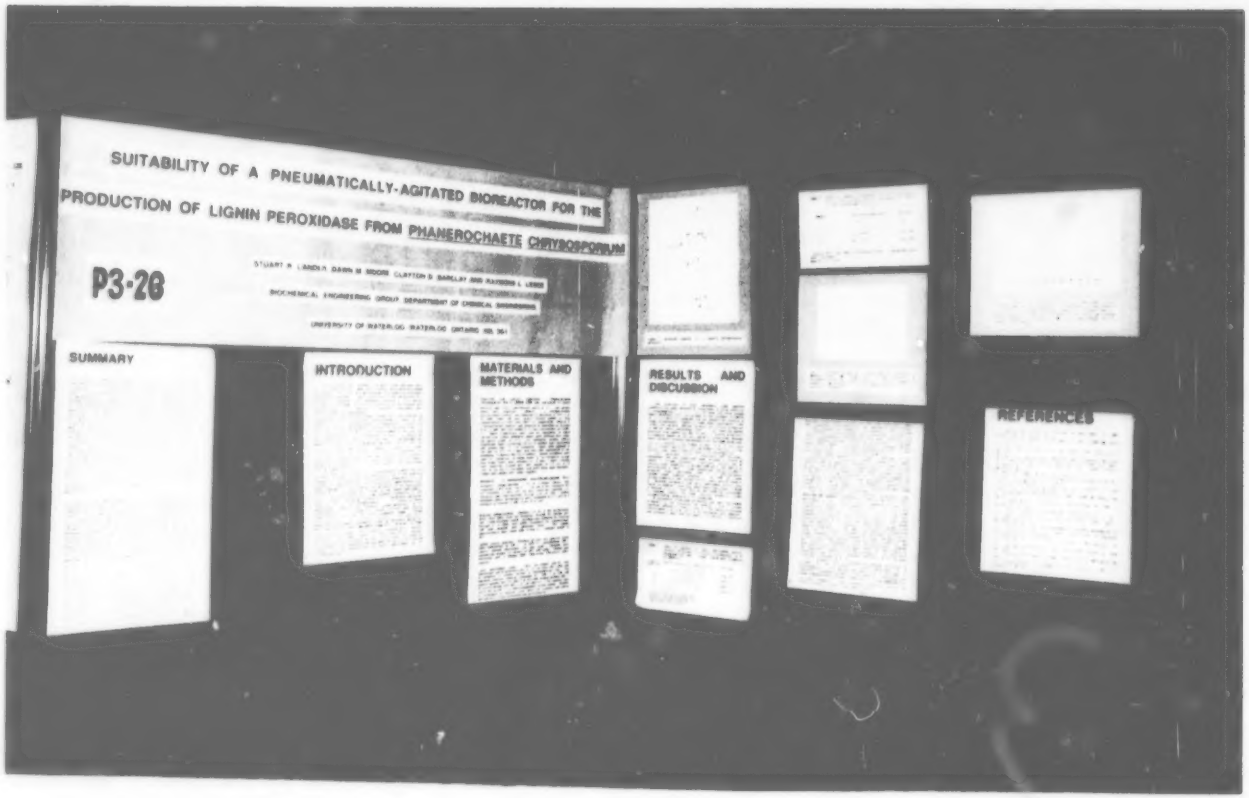
SUITABILITY OF A PNEUMATICALLY-AGITATED BIOREACTOR FOR THE PRODUCTION OF LIGNIN PEROXIDASE FROM PHANEROCHAETE CHRYSOSPORIUM
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SUITABILITY OF A PNEUMATICALLY-AGITATED BIOREACTOR FOR THE PRODUCTION OF LIGNIN PEROXIDASE FROM PHANEROCHATE CHRYSOSPORIUM

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The efficient saccharification of cellulose in lignocellulosic feedstocks requires pretreatment to modify or remove the lignin component. The pretreatment contributes significantly to the cost of lignocellulosic bioconversion processes. The biodegradation of lignin by the ligninolytic enzyme system of Phanerochaete chrysosporium may offer an alternate technology for the pretreatment of these feedstocks. Development of this technology is hampered by problems associated with the scale-up of the production of the enzyme system. The suitability of using a low shear pneumatically-agitated bioreactor, of in-house design, has been examined. Using P. chrysosporium INA-12, selected media and mixing conditions favour the formation of pellets averaging 2-4 mm in diameter and a biomass concentration of 1.2 - 5 g/L. Lignin peroxidase activity is based on the hydrogen peroxide-dependent oxidation of veratryl alcohol to veratraldehyde. Levels of 80 units/L are routinely obtained with this device although levels as high as 180 units/L have been achieved. The enzyme activity is non-growth associated; peaks 7- 8 days after inoculation and rapidly decays. Heat denaturation studies suggest that the enzyme is thermally stable at 37°C. The loss of activity may be attributed to inactivation of the lignin peroxidases by proteolytic action or hydrogen peroxide. Enzyme production under agitated conditions is dependent on media composition and inoculation procedures and cannot be predicted based on static culture performance.

Pour saccharifier efficacement la cellulose de matières de départ lignocellulosiques, il faut appliquer un prétraitement visant à modifier ou à éliminer la lignine. Ce prétraitement fait beaucoup monter le coût des procédés de bioconversion lignocellulosique. La biodégradation de la lignine par le système enzymatique ligninolytique de Phanerochaete chrysosporium pourrait être utilisée comme autre technique pour le prétraitement de ces matières de départ. La mise au point de cette technique est toutefois gênée par des problème liés à la mise à l'échelle du système enzymatique. On a étudié l'utilité d'un bioréacteur à faible déformation de cisaillement, à agitation pneumatique, de conception domestique. L'utilisation de P. chrysosporium INA-12, de certains milieux et de certaines conditions d'agitation favorise la formation de pellets présentant en moyenne un diamètre de 2-4 mm et une concentration de biomasse de 1,2-5 g/L. L'activité de la lignine peroxydase est basée sur l'oxydation, liée au peroxyde d'hydrogène, de l'alcool vératrylique en vératraldéhyde. De cette facon, on obtient régulièrement des concentrations de 80 unités/L, mais on a déjà obtenu jusqu'à 180 unités/L. L'activité de l'enzyme n'est pas liée à la croissance; elle atteint un maximum 7-8 jours après l'inoculation, puis elle diminue rapidement. Des études portant sur la dénaturation thermique montrent que l'enzyme est stable thermiquement à 37°C. La perte d'activité peut être attribuée à l'inactivation des lignines peroxydases soumises à un effet protéolytique ou à l'action du peroxyde d'hydrogène. La production d'enzyme en présence d'agitation dépend de la composition du milieu et des méthodes d'inoculation. Elle ne peut être prévue d'après le rendement en culture statique.

INTRODUCTION

The successful biodegradation of lignin could alleviate many of the problems associated with existing lignocellulosic-based processes. The successful development of a selective enzymatic degradation process for lignin could result in the production of a number of valuable and renewable aromatics. This would contribute advantageously to the economics of the process and would result in the reduction of pollution associated with chemical bleaching operations.

Several organisms have been studied for their potential to biodegrade lignin. The best characterized of these is the white-rot fungus, Phanerochaete chrysosporium. Since the discovery of lignin peroxidase (ligninase) by Tien and Kirk (16) and Glenn et al. (4), research has concentrated on the role that this enzyme plays in the degradation of lignin. It should be appreciated that in addition to ligninase, P. chrysosoporium secretes many other extracellular enzymes which may be involved in lignin degradation. Indeed it appears that these enzymes function in concert and that a complement or "ligninolytic cocktail" may be required for many of the practical applications envisioned for this enzyme system. For this reason production strategies which focus exclusively on the ligninases may be inadequate.

The large scale production of the ligninolytic system has not yet been achieved and this has served as one of the practical problems in the assessment of its industrial application (15). A number of traditional and novel fermentation approaches have been assessed for the scale-up and elicitation

of the ligninolytic system by P. chrysosporium. These include media optimization (10, 17), cell permeabilization under agitated conditions (5), the use of rotating biological contactors (7), membrane perfusion reactors (18), and cell immobilization (11, 12). Some of these approaches address the apparent shear-sensitivity of P. chrysosporium. In bioreactors, oxygen transfer and mixing requirements must be met with acceptable shear. These requirements are often mutually contradictory. Pneumatically-agitated bioreactors offer an attractive option for the scale-up of shear sensitive organisms because of their hydrodynamics, shear and mixing characteristics. Recent advances have been made in their engineering design, facilitating scale-up of these devices. In this paper we report on the suitability of a pneumatically-agitated bioreactor, of in-house design, for the production of lignin peroxidase by P. chrysosporium.

MATERIALS AND METHODS

Organism and Culture Conditions: Phanerochaete chrysosporium INA-12 (CNCM I-398) was maintained on potato dextrose agar (Difco Laboratories) slants at 4°C. Two growth media were employed. Medium I, a nitrogen-limited, glucose-based medium, was prepared as described by Kirk et al. (8) with Tween 80 and veratryl alcohol added to final concentrations of 0.04% and 0.003% v/v, respectively. Medium II, a glycerol-based medium, was prepared as described by Buswell et al. (2) with oleic acid added to a final concentration of 0.045% v/v. Spore suspensions were used for inoculation of liquid cultures and, unless otherwise stated, were obtained from 4-day old slants grown at 37°C. For bioreactor studies, 500-ml Erlenmeyer flasks containing 100 ml of medium were inoculated with greater than 2.0 x 10^7 spores/ml. Flasks were agitated at 160 rpm for 37°C for 2 days and were then transferred to the bioreactor containing 800 ml of medium. Similar conditions were used for comparison of shake flasks to the bioreactor except that shake flasks were followed for 10 days. Static cultures were aseptically flushed with 100% oxygen for 1.5 min at 10 l/min on the day of inoculation and every three days thereafter. Flasks were sealed with rubber stoppers.

Bioreactor: A slanted-bottom pneumatically-agitated Pyrex bioreactor (height:diameter = 4) of in-house design was employed in this study (Figure 1). The use of this bioreactor for the cultivation of plant cells has been previously reported (14). House-air was filter-sterilized through 0.22 µm filter. Unless otherwise stated, fermentations were conducted at 37°C and at a constant air flowrate of 400 ml/min (0.44 vvm).

Biomass measurements: Samples (13 ml) of the fermentation broth were taken from the bioreactor through the sample port with a wide-mouthed pipette. Biomass was collected by filtration through 15 µm Nitex cloth (B&SH Thompson Co., Scarborough, ON) and washed with deionized water. Dry weight determinations were made after drying to a constant weight at 60°C.

Carbon source analysis: Residual glucose and glycerol levels were determined by HPLC. A HPX-87C carbohydrate HPLC column (Biorad, Richmond, CA) was used. Samples were isocratically eluted (1.0 ml/min) at 90°C with water. Elution was monitored with a Waters R401 Differential Refractive Index Detector.

Lignin peroxidase assay: Lignin peroxidase activity was determined spectrophometrically at 310 nm from the initial rate of oxidation of veratryl alcohol to veratraldehyde (16). The standard reaction mixture consisted of: 300 µl of 166 mM sodium tartrate (pH 3.0), 200 µl of 10.4 mM veratryl alcohol, 200 µl of culture filtrate and 300 µl of 1.35 mM H_2O_2. The reaction was conducted at 26°C in a thermoregulated cuvette holder. Activity is expressed in enzyme units, with one enzyme unit being defined as 1 µmole veratraldehyde produced/min.

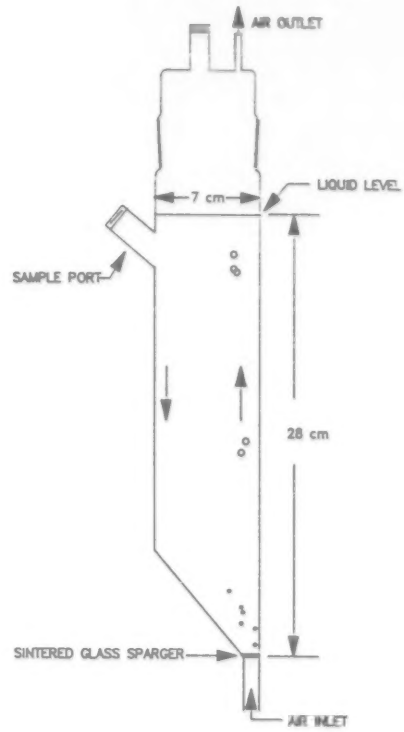

Figure 1. Schematic diagram of a 1-l capacity slanted-bottom bioreactor.

RESULTS AND DISCUSSION

The production of lignin peroxidase under agitated conditions has been reported by researchers for three strains of P. chrysosporium (1, 3, 5, 9 - 12). Of these only three groups report conditions which are suitable for the formation of pellets (9 - 12, 17) which are desirable and can simplify the scale-up of fungal fermentations. Based on shake flask experiments it was evident that agitation affected biomass and enzyme production as well as culture morphology (Table 1). Low rotational speeds produced large pellets but did not result in enzyme production. A rotational speed of 160 rpm offered a compromise between pellet formation, biomass concentration and ligninase production. This is in contrast to the finding of Jager et al. (5) who were able to achieve significant lignin peroxidase

Table 1. Effect of agitation on lignin peroxidase activity, biomass production and culture morphology of P. chrysosporium (INA-12) under submerged conditions for Medium I.

Rotational Speed (rpm)	Lignin Peroxidase Activity U/l	Maximum Biomass g dr.wt./l	Morphology
0	149 (7)*	6.05 (21)	single mycelium
130	0*	1.30 (11)	pellets (3.5)
160	117 (8)*	1.20 (10)	pellets (2.5)
200	0*	0.20 (7)	pellets (1.5)

* Cultures (50 ml per 500-ml Erlenmeyer flask)
* Cultures (75 ml per 500-ml Erlenmeyer flask)
( ) designates mean pellet diameter (mm)
( ) designates days after inoculation

production at high agitation rates, using a different strain of P. chrysosporium.

Lignin peroxidase activity is associated with secondary metabolism and has traditionally been initiated in culture by carbon or nitrogen limitation. Ligninolytic activity can be induced under conditions of nitrogen-sufficiency with INA-12 as demonstrated in Table 2. Static submerged cultures of INA-12 produced lignin peroxidase both in a glucose-based, nitrogen-limited medium (medium I) as well as under nitrogen-sufficiency with glycerol as the carbon source (medium II). Biomass production and lignin peroxidase activity were higher for medium II and these observations are similar to those of Buswell et al. (2). Given that the two media are comparable in available carbon, the lower biomass production under nitrogen-limiting conditions is not unexpected.

Table 2. Effect of medium composition on lignin peroxidase activity and biomass from P. chrysosporium (INA-12) in static submerged cultures.

Medium	Lignin Peroxidase Activity U/l	Biomass g/l
I	113 ± 20(7)	3.23±0.66
II	255 ± 36(7)	4.55±0.90

Cultures (50 ml per 500-ml Erlenmeyer flask; ( ) designates days after inoculation. Means ± s.e. (n=4).

A comparison of biomass production and lignin peroxidase production in the bioreactor for medium I and II reveals significant differences (Figure 2 and 3). The maximum biomass concentration (1.55 g dr. wt./l) in the bioreactor with medium I was achieved 3 days after inoculation. In contrast, a maximum biomass concentration of 5.86 g dr. wt./l was achieved 4 days after inoculation, with medium II. This represents approximately a 4-fold increase over medium I. Fluctuations in the biomass concentration for the bioreactor can be attributed to problems in obtaining representative samples as pellet size, morphology and broth rheology changes during the fermentation. In agitated shake flasks (medium I) biomass production increased steadily from day 2 to day 10. Biomass concentrations on day 10 were twice those found in the bioreactor with medium I.

Carbon uptake parallels the increase in biomass for both sources (Figure 3). The glycerol content of medium II is rapidly depleted and its depletion correlates with the initiation of the plateau in the growth curve. Glucose uptake is similar for both shake flasks and the bioreactor even though biomass production is different for the two configurations. This might suggest that the degree of hydrodynamic shear generated under the two configurations has an impact on the metabolic proportioning of carbon for this fungal system. Similar observations were made for plant cell cultures using this bioreactor (14).

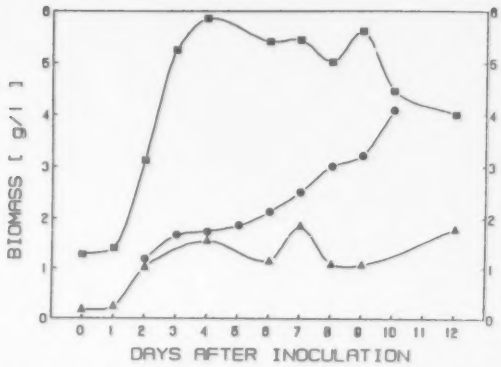

Figure 2. Biomass production in shake flask and bioreactor for Medium I and II. (●) Shake flask (160 rpm), medium I; (▼) bioreactor (0.44 vvm, spore inoculum = 2.5×10^6 spores/ml), medium I; (■) bioreactor (0.44 vvm, spore inoculum = 2.5×10^6 spores/ml), medium II.

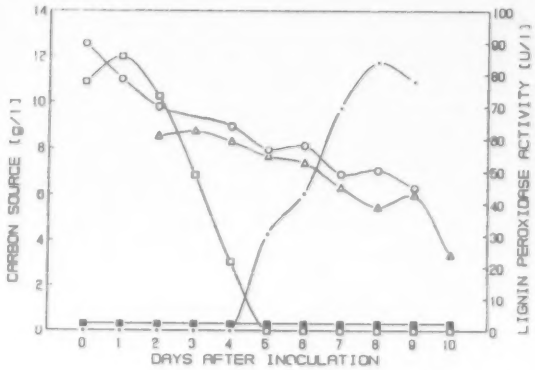

Figure 3. Carbon source utilization and lignin peroxidase activity in shake flask and the bioreactor. (○) Residual glucose, medium I, bioreactor; (▽) residual glucose, medium I, shake flask; (□) residual glycerol, medium II, bioreactor; (●) lignin peroxidase activity, medium I, bioreactor; (■) lignin peroxidase activity, medium II, bioreactor.

The most significant effect of medium composition under pneumatically-agitated conditions was seen in the level of lignin peroxidase activity. Enzyme activity appeared 5 days after inoculation in medium I and peaked on day 8. No activity was observed for medium II in the bioreactor (Figure 3) or under agitated conditions (data not presented). Typically under static conditions for medium I and II, activity appears 5 days after inoculation, peaks at day 7 and then rapidly decays. The reason for the difference in response to pneumatic agitation and medium composition is not clear. At least two possibilities exist. The high biomass achieved in the bioreactor may result in oxygen limitation. This is important as oxygen has been shown to play a part in the regulation of the ligninolytic system (6). We are currently investigating the interrelationship between dissolved oxygen and hydrodynamic shear and their effects on the ligninolytic system using this bioreactor. An alternative explanation may be carbon catabolite repression which has been proposed by Buswell et al. (2).

It is apparent that a pneumatically-agitated bioreactor is suitable for the production of lignin peroxidase by P. chrysosporium. The device described here is amenable to laboratory investigations and for the study of P. chrysosporium under pneumatically-agitated conditions. It is also apparent that ligninase production under agitated conditions cannot be predicted based on static culture performance.

ACKNOWLEDGEMENTS

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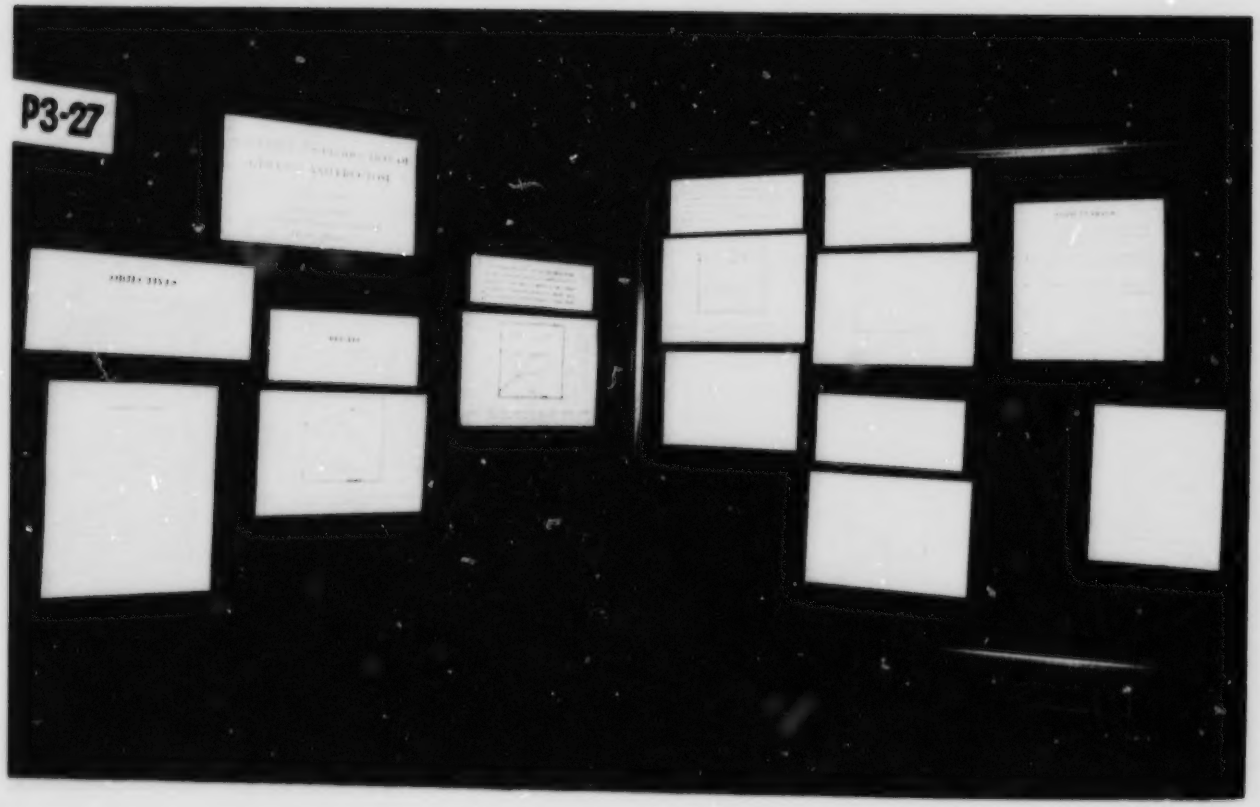
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SIMULTANEOUS PRODUCTION OF ETHANOL AND FRUCTOSE

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The viability of the ethanol production industry can be enhanced considerably by the simultaneous production of other valuable products. This can be accomplished when fermentation is carried out with solutions containing both glucose and fructose. Since fructose is very valuable as a sweetener such a mixture would be utilized well if only the glucose were converted to ethanol and the fructose were left unconverted. This selective fermentation has been carried out with molds, bacteria and yeast.
In this work yeast is used to produce ethanol and fructose batchwise, semicontinuously and continuously from high fructose corn syrup (HFCS) and hydrolyzed Jerusalem artichoke juice. Batch experiments carried out with a mixture of these two products produced 8.3% w/v ethanol and 18.8% w/v fructose from an original solution of 18.4% w/v glucose and 19.8% w/v fructose in 11 hours. By the continuous addition of HFCS to a yeast slurry more than 10% w/v ethanol was formed while fructose accumulated to 16.3% w/v. Immobilization of the yeast in Ca-alginate beads and utilization in a packed bed reactor was also carried out. In this system 7.4% w/v ethanol was produced from a mixture of HFCS and Jerusalem artichoke juice.

La viabilité de l'industrie de l'éthanol peut être considérablement accrue par la production simultanée d'autres produits utiles. Cette production simultanée est possible lorsque la fermentation est réalisée avec des solutions contenant du glucose et du fructose. Comme le fructose est un édulcorant très utile, un tel mélange pourrait être exploité à fond si seul le glucose était transformé en éthanol et que le fructose restait inchangé. Cette fermentation sélective a été réalisée avec des moisissures, des bactéries et des levures.
Dans ces travaux, on utilise une levure pour produire de l'étahnol et du fructose par fermentation en lot, en semi-continu et en continu de sirop de maïs riche en fructose et de just de topinambour hydrolysé. Les expériences en lot réalisés avec une mélange de ces deux produits ont permis d'obtenir, en 11 heures, 8.3% (pds/vol) d'éthanol et 18.8% (pds/vol) de fructose à partir d'une solution contenant au départ 18.4% (pds/vol) de glucose et 19.8% (pds/vol) de fructose. En ajoutant en continu le sirop de maïs riche en fructose à une bouillie de levure, on obtenait plus de 10% (pds/vol) d'éthanol, tandis que le fructose s'accumulait jusqu'à 16.3% (pds/vol). On a aussi immobilisé la levure dans des capsules d'alginate de calcium et on a utilisé un réacteur à lit tassé. On produisait dans ce système 7.4% (pds/vol) d'éthanol à partir d'un mélange de sirop de maïs riche en fructose et de jus de topinambour.

INTRODUCTION

The viability of the ethanol production industry can be enhanced considerably by the simultaneous production of other valuable products. One such possibility exists for the fermentation of solutions containing both glucose and fructose. Both of these carbohydrates can be used as substrate for ethanol production by all conventional ethanol producing microbes (1). Since fructose is very valuable as a sweetener (2 3), the food industry is very interested in fructose syrups which would contain a higher percentage of fructose than in conventional high fructose syrups. The separation of glucose from glucose-fructose mixtures is quite expensive by the existing technologies. An alternative is to selectively ferment glucose to ethanol from such mixtures and to leave fructose unconverted. Thus, two valuable products

would be available, ethanol and fructose, which could be separated by distillation. This selective fermentation has been carried out with Tricholoma nudum (4), a mycelial fungal system (5), Zymomonas mobilis (6) and a Saccharomyces cerevisiae mutant (7).

In this work the yeast (7) is used to produce ethanol, and very enriched fructose syrup batchwise, semicontinuously and continuously from high fructose corn syrup (HFCS) supplemented with Jerusalem artichoke juice.

MATERIALS AND METHODS

The inoculum medium used for the propagation of Saccharomyces cerevisiae (ATCC 36859) consisted of glucose (10.0 g), yeast extract (30.0 g), peptone (3.5 g), KH_2PO_4 (2.0 g), $MgSO_4.7H_2O$ (1.0 g), $(NH_4)_2SO_4$ (1.0 g) and distilled water (up to 1 litre). One of the intentions of this work was to use only food grade materials, without adding any chemicals to the medium for the production of ethanol, and fructose which would be used for human consumption. Therefore, high fructose corn syrup (HFCS) and Jerusalem artichoke juice were chosen. The high fructose corn syrup used in this study contained 46% w/v glucose and 35% w/v fructose. Hydrolized Jerusalem artichoke juice (4% w/v glucose and 17% w/v fructose) was prepared as described previously (7) and served together with HFCS as a source of all nutrients for the yeast in the processes for alcohol and fructose syrup production. The concentrations of the J. artichoke juice was kept as low as possible in order to facilitate purification of the fructose syrup. All fermentations were carried out at 33°C.

The ethanol concentration was determined enzymatically using alcohol dehydrogenase (8). Fructose and glucose concentrations were determined with a Waters high performance liquid chromatograph with a Sugar Pak column at 80°C using deionized water. Biomass was measured by weighing, after overnight drying in an oven, a known volume of sample.

RESULTS AND DISCUSSION

The first test of ethanol and enriched fructose syrup production was carried out using a medium containing 22 mL of HFCS, 5 mL of hydrolized Jerusalem artichoke juice and 73 mL of water in a 500 mL Erlenmeyer flask. In the process, the glucose (10.2% w/v) was converted to 4.7% (w/v) ethanol in 11 hours; this represents 90% of the ethanol theoretical yield (Fig. 1).

To increase the ethanol concentration, the HFCS content of the medium was increased to about 50%. This time, the process was carried out with a much larger biomass concentration in order to decrease the process time, and with 10% of Jerusalem artichoke juice in the medium to supply the increased amount of cells with a sufficient quantity of nutrients other than

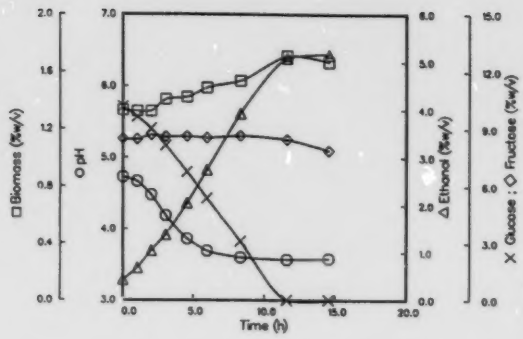

Figure 1 Batch ethanol production from a mixture of HFCS and Jerusalem artichoke juice (5% v/v)

the carbon source. The results show (Fig. 2) that all of the glucose (15% w/v) was used in 3 hours to yield 6.6% (w/v) ethanol which corresponds to 86% of the theoretical value.

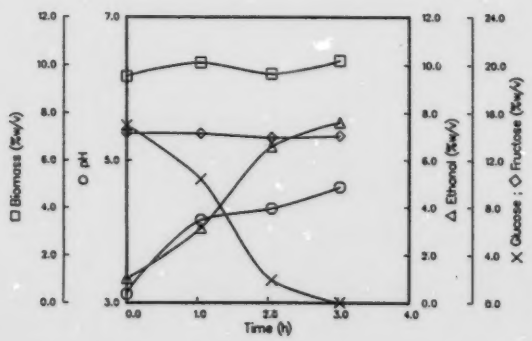

Figure 2 Batch ethanol production from a mixture of HFCS and Jerusalem artichoke juice (10% v/v).

Most of the biomass from the preceding batch was then separated and transferred to fresh medium made of an increased amount of HFCS and 10% J. artichoke juice. The resultant mixture, after adding the biomass slurry which contained some ethanol and fructose, contained 18.4% (w/v) glucose and 19.8% (w/v) fructose. In this process the glucose was utilized in 8 hours, and the produced broth contained 10.8% (w/v) ethanol and 18.8 (w/v) fructose. Subtracting the amount of ethanol added with the inoculum, the ethanol yield was about 88% of the theoretical value. Unlike the previous two batch tests in which no fructose was consumed the results show a 5% reduction in its concentration (Fig. 3).

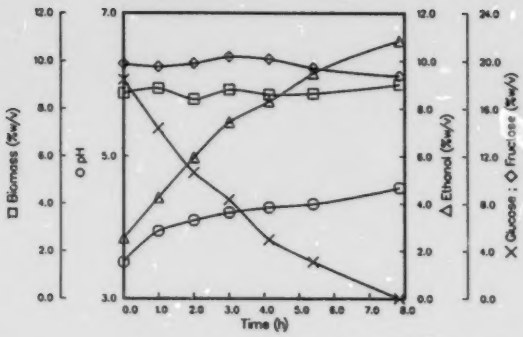

Figure 3 Batch ethanol production from a mixture of HFCS and Jerusalem artichoke juice (10% v/v). The biomass from the previous test (Fig. 2) was used in this process with a higher HFCS conc.

In the last two tests the same biomass was used but its initial concentrations were different. To see the biomass activity after it has been already once used and to compare it with its initial activity, the specific ethanol productivities were calculated. Bearing in mind that the final ethanol concentrations differed substantially (7.6% and 10.8%) the productivities for the first hour of both processes were taken. The data in Table 1 show that the specific ethanol productivity of the biomass is decreased by about 5% when it is used the second time. This reduction may be caused by the higher (30%) carbohydrate concentration in the last test.

Table 1. Initial specific ethanol productivities

Glucose (% w/v)	Fructose (% w/v)	Ethanol Productivities[a] (% w/v/h/g biomass)
15.0	14.3	0.207
18.4	19.8	0.196

[a]Productivities calculated from ethanol production in first hour of test.

In all these tests fermentation broths were produced which contained ethanol and fructose in high concentrations. Upon removal of the ethanol the fructose syrup would contain no glucose.

The results of a semicontinuous fermentation are shown in Fig. 4. In this test a yeast slurry of approximately 275 mL was transferred to a stirred tank bioreactor. To this, a mixture of 37.0% w/v glucose and 31.0% w/v fructose (composed of HFCS and 10% v/v J. artichoke juice) was added at a rate of 40 mL/h. Sterilization of this mixture was not necessary because the solid content was nearly 70%. The yeast converted the added glucose to ethanol while the fructose was unused. After 5 hours the ethanol concentration increased to 7.3% w/v while the fructose accumulated to 12.0% w/v. The concentration of ethanol started to level off because the activity of the cells was decreasing due to a high ethanol and a high carbohydrate (fructose) concentration, and a lack of oxygen. Consequently, further additions of HFCS and juice resulted in the accumulation of some glucose. To prevent build-up of the glucose concentration in the reactor mixture, the addition of HFCS and juice was stopped 10 hours after the beginning of the test; at that time the glucose concentration was already 5.3% w/v.

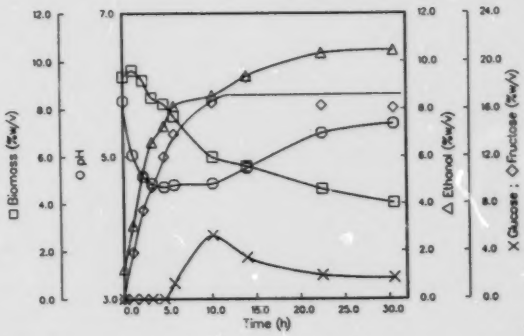

Figure 4 Semicontinuous ethanol production in a stirred tank reactor with a continuous addition of a feed containing 37% w/v glucose and 31% w/v fructose.

Up to that moment the process was carried out without the introduction of air. But after, when the medium addition was ceased, air was introduced in an attempt to stimulate the yeast's activity. The results in Fig. 4 show that the amount of biomass increased by about 58% in the first 10 hours, but after that its amount started decreasing. Despite the decrease in the biomass quantity after the aeration process started, a reduction of the glucose and an increase in the ethanol concentrations were noticed. The glucose concentration was reduced to 1.7% w/v after 13 hours of aeration. Some fructose was also consumed during the last several hours of the process. After 23 hours the solution contained 10.3% w/v ethanol as well as 16.3% w/v fructose and 1.7% w/v glucose.

The continuous production of ethanol and fructose was carried out with immobilized cells. The cells were encapsulated in calcium alginate beads (3±0.2 mm diameter) and placed in a packed bed reactor (3.1 cm I.D., 11.5 cm long). The medium which contained 15.1% w/v glucose and 13.6% w/v fructose was pumped continuously into the bottom of the reactor. At a dilution rate of 0.180 h^{-1} the product contained 5.3% w/v ethanol, 12.6% w/v fructose and 4.7% w/v glucose (Fig. 5).

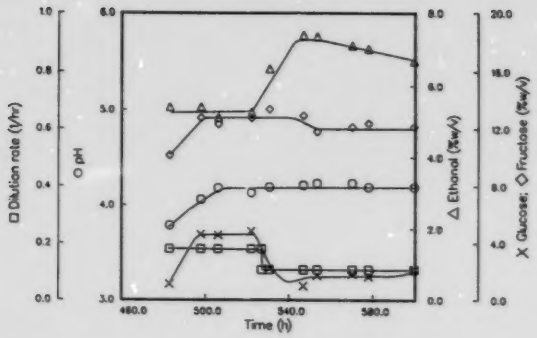

Figure 5 Continuous ethanol production in a packed bed reactor with immobilized cells using a feed containing 15.1% w/v glucose and 13.6% w/v fructose.

A decrease in the dilution rate to 0.106 h^{-1} resulted in an increase in the ethanol concentration to 7.4% w/v and a decrease in the glucose concentration to 1.3% w/v. The activity of the beads started to decline slowly at this flow rate probably due to the high ethanol concentration in the reactor, and to the fact that they have been already used for more than 500 hours.

CONCLUSIONS

The results have shown the simultaneous production of fructose syrup and ethanol batchwise, semicontinuously and continuously.

Tests carried out batchwise have demonstrated the complete conversion of glucose to ethanol and biomass from mixtures of high fructose corn syrup and Jerusalem artichoke juice. Thus, the final solution contained ethanol, and fructose as the only carbohydrate.

Using a semicontinuous system high fructose concentrations can be obtained by the continuous addition of a mixture containing HFCS and juice to a yeast slurry in which the glucose was converted to ethanol (10.3 w/v) and the fructose accumulated to 16.3 w/v (0.89 of the total reducing sugars).

In a continuous system employing immobilized cells in a packed bed reactor 7.4% w/v ethanol was produced while the fructose fraction of the reducing sugars was increased from 0.47 in the initial medium to 0.91 in the final product.

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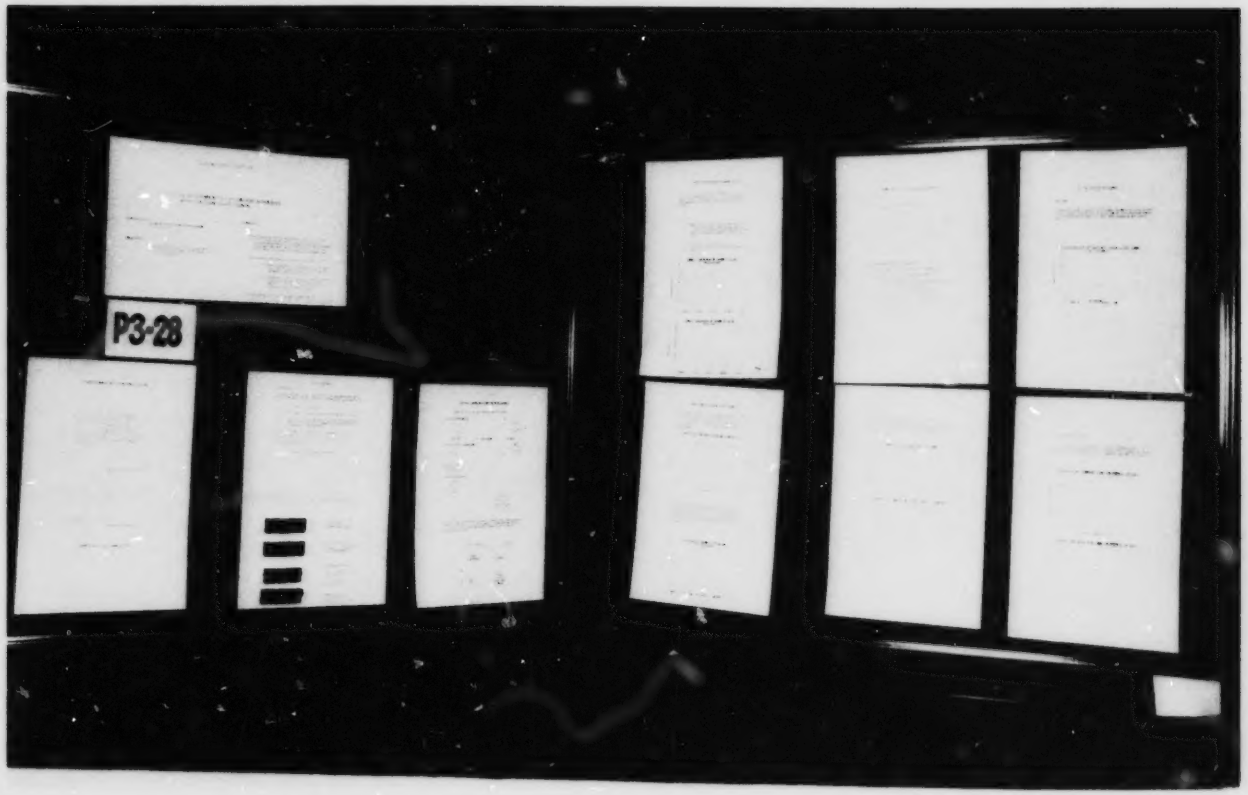
P3-28

THE USE OF LIGNIN IN PLYWOOD ADHESIVES

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This paper describes the use of Exploded Wood lignin as a component of a plywood adhesive. Exploded Wood lignin was used in an unmodified (UM) form, and after chemical modification. The UM lignin is from steam-exploded aspen wood which has been further digested by cellulase enzymes. The chemical modification included reaction of the lignin with phenol, reaction with formaldehyde, oxidation at alkali conditions, and acid precipitation of the lignin to remove the cellulose. Although these reactions have been reported for commercial materials such as Kraft lignin, there is little information available on the chemical modification of steam-exploded lignin and its use in plywood adhesives. Steam-exploded lignin might be particularly well suited to these applications because of its low molecular weight and the absence of interfering side groups.

Commercial plywood adhesives consist of a resin, which is a liquid crosslinked polymer, as the primary adhesive network former. The most common resin is made with phenol and formaldehyde (P/F). Other components of the commercial adhesives include fillers, extenders, and water, which affect the viscosity and penetration of the glue, and a catalyst, which hastens the curing reaction UM and chemically modified lignin were added to the glue in two ways: a) direct addition of the lignin to the glue formulation, and b) reaction of the lignin with phenol and formaldehyde during resin synthesis. In both applications a) and b), the lignin replaced up to 50% of the phenol. In all cases, the resulting glues were used to make plywood boards, which were tested and compared with boards made from commercial plywood glues.

INTRODUCTION

Lignin is one of the most abundant natural products on earth. It is a major component of all plants with a content ranging from 3% in corn stalks, to 33% in softwoods. Any large scale biomass conversion project necessitates a market for the lignin, both to increase the total product revenues and to avert a waste disposal problem.

Only a fraction of the lignin recovered from the pulp and paper industry, the largest producers of lignin, is converted to commercial products. Because of its low value, the majority is burned on site to produce energy and recovery pulping chemicals.

The unique characteristics of this steam exploded lignin make it an ideal starting material for manufacture of high value products. Techtrol Steam Exploded Lignin has been shown to have a higher potential than other lignins for use as a polymer network former (Glasser et.al. 1983). Its narrow molecular weight distribution, coupled with its low degree of condensation and interunit linkages enable steam exploded lignin to incorporate itself into phenol formaldehyde structures.

Lignins are used for the production of a wide range of chemicals and materials. Some of their industrial surfactant applications include drilling muds, animal feed binders, gypsum board and construction materials, concrete and cement admixtures, and dust control and soil stabilization agents. Other markets for lignin include rubber reinforcement agents, asphalt extenders, and a vanillin precursor.

Lignin based adhesives are among the most widely studied products. One of lignin's large uses could be as a major constituent in phenol formaldehyde thermosetting resins. These resins are used for particle board, plywood, foundry binders, laminates, and in the production of insulating materials. In these applications, lignin and/or phenol is condensed with formaldehyde to form a stiff resin matrix. Existing commercial lignins have not had major success in entering these markets. Their low reactivity leads to uneconomically long cure times for adequate resin set. They have to date only been used in small quantities as resin extenders.

Plywood adhesives are the largest single application of phenolic resins in North America, using 500 million pounds in 1983, more than all the other wood products combined. While other

products such as waferboard and oriented strand board (OSB) are taking some of the plywood market, estimates by SRI of phenolic resin usage for the near future show plywood continuing to consume more than the total of all other wood products combined.

Lignin's similarity in structure and bonding to a PF resin condensate suggests it could be an effective substitute for phenol formaldehyde resin. In a phenol formaldehyde resin, formaldehyde is used to form methylene links between phenols to produce a rigid matrix. In lignin, the three building blocks are connected to one another using various linkages including methylene links. The lignin can also be condensed with phenol by using formaldehyde.

Plywood glues are multicomponent systems who major constituent is phenol/formaldehyde resin. Plywood mills combine the resins with powdered fillers, extenders, catalysts, and water on site to form a glue. The resin is the primary adhesive network former, with a catalyst added to hasten the reaction. Fillers, extenders and water are added to adjust the viscosity of the glue to the proper value for spreading, modify penetration into the wood, and reduce the cost of the glue.

Techtrol's steam exploded lignin can be added to glues in powdered form at the plywood plant, along with extenders and fillers causing no change in the practice of mixing glues. Its high reactivity allows it to directly replace phenol/formaldehyde instead of just acting as an inert filler (Foody, et.al. 1986). The lignin is obtained as a water insoluble, caustic soluble residue from the enzymatic hydrolysis of steam exploded wood, to a cellulose conversion of 85%. The lignin has a methoxyl content of at least 15.0% and is dried to a powder.

The testing and development of new glue formulations is a highly labor intensive process. Current testing by CSA standard procedures take two to four man days per glue. As well, wood failure results are highly dependent on the properties of the particular batch of wood and particular log the veneer came from, causing the need for many replicates in testing to ensure statistical accuracy of results.

Chemical modifications to lignin have been widely studied and shown to improve lignin performance (Sarkanen et.al. 1971). Steam exploded lignin could be improved by chemically reacting ti before incorporation into a glue. This would lead to higher PF substitutions and improved economic value. Four different chemistries will be investigated: hydroxymethylation, phenolation, coreaction with phenol formaldehyde condensate, and demethylation.

Hydroxymethylation (or methylolation) of lignin is a reaction between lignin and formaldehyde wherein methylol groups are attached to the reactive sites of the lignin. These groups can then cross link more effectively with a PF resin complex during the final cure of a glue. The literature suggests the preferred conditions for hydroxymethylation are at an alkaline pH and room or slightly elevated temperatures (Clarke and Dolenko 1978, Lin 1980, Dilling 1985).

Phenolation of lignin is a reaction between lignin and phenol wherein highly rea tive phenol is bound to the lignin thereby increasing its overall reactivity. Phenolation has been used as a method of dissolving the lignin and is normally performed under acid conditions (Sarkanen 1971).

Incorporating lignin in the PF resin manufacturing process via coreaction with phenol and formaldehyde may lead to improvements in performance. There is a priori reason to anticipate that lignin added to a precured commercial resin formulation, as was done in the mill trial, is the best choice. The system may be suffering from a shortage of formaldehyde for resin crosslinking. Alternatively lignin's lower reactivity may be best countered by giving it the opportunity to react with the PF resin complex throughout the precure period. Early testing at Reichhold Chemicals (Jenkins 1983) suggested that inclusion of the lignin in the resin preparation procedure will lead to improved performance.

Methoxyl groups on lignin block potential reactive sites on the aromatic ring, decreasing the lignins ability to crosslink. Demethylation will remove these methoxyl units and open up more reactive sites on the lignin (Dence et.al. 1960, Goheen 1962, Sarkanen 1971). This procedures is usually done in the presence of chloride ions in acid or alkaline conditions (White et.al. 1941).

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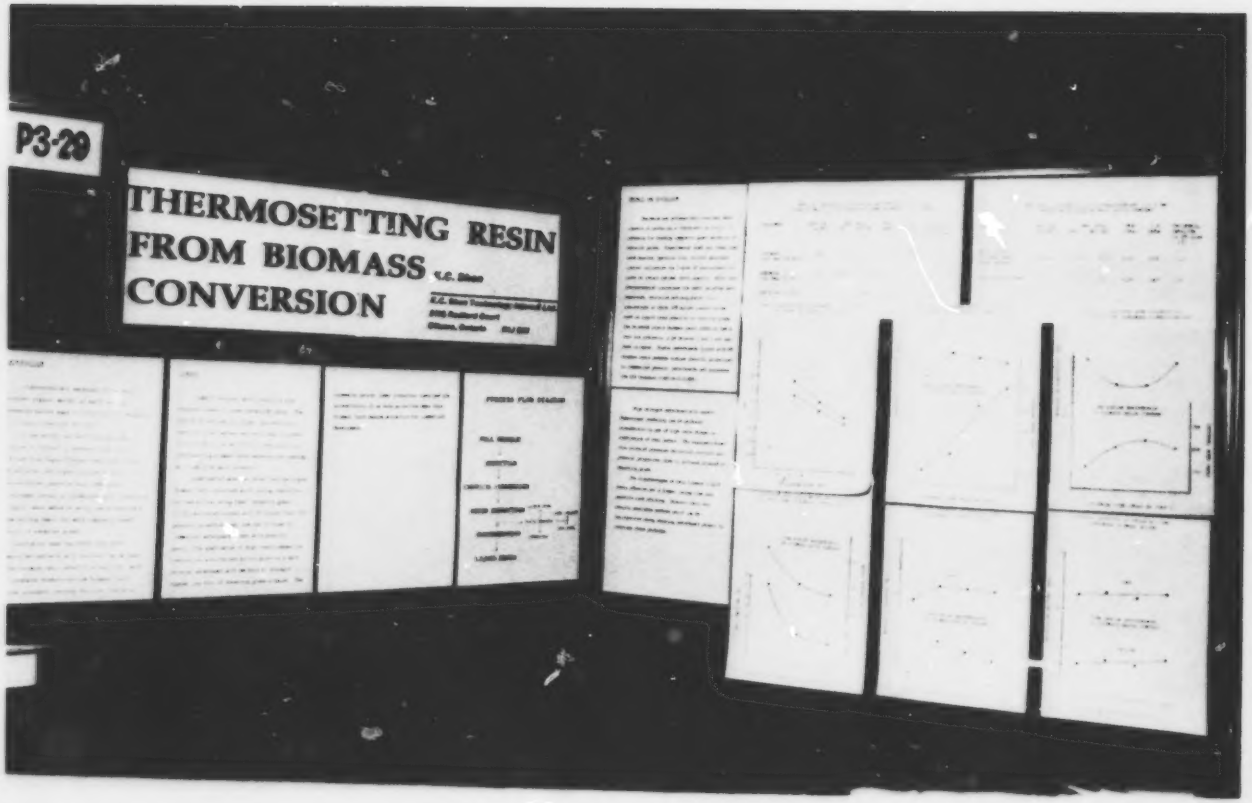
P3-29
THERMOSETTING RESIN
FROM BIOMASS
CONVERSION

THERMOSETTING RESIN FROM BIOMASS CONVERSION

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Lignocellulosic material can be thermochemically converted to generate a thermosetting resin adhesive for bonding wood composite products. Sawmill residues of single or mixed species in dry or wet condition are treated to high pressure steam to cause thermohydrolysis. The hemicellulose portion of the lignocellulosic material is decomposed and hydrolyzed to water solubles containing mainly low molecular weight carbohydrates and other decomposition products. The water solubles can be filtered and separated from the treated residue in liquid form, which then can be evaporated into a concentration of about 45-50% solids and used as a thermosetting resin binder for wood composite panel products.

Il est possible, par voie thermochimique, d'obtenir à partir de matières lignocellulosiques un ahesif constitué d'une resine thermodurcissable utilisable dans la fabrication d'agglomérés de bois. On traite les résidues de sciage de bois d'une seule ou de plusieures espèces avec de la vapeur sous pression élevée dans des conditions sèches ou humides, afin de réaliser la thermohydrolyse. On décompose la fraction hemicelluloosique des matières lignocellulosic, puis on l'hydrolyse en matières hydrosolubles renfermant surtout des glucides de faible masse moleculaire refermant surtout des glucides de faible mass moleculaire et d'autres produits de decompostions. On filtre les matières hydrosolubles, puis on les sépare du residue traité sous forme d'un liquide qui peut ensuite être concentré par évaporation jusqu'a une teneur de 45-50% en solides; ce liquide peut ensuite être utulisé comme liant thermodurcissable pour fabriqué des panneaux agglomérés.

INTRODUCTION

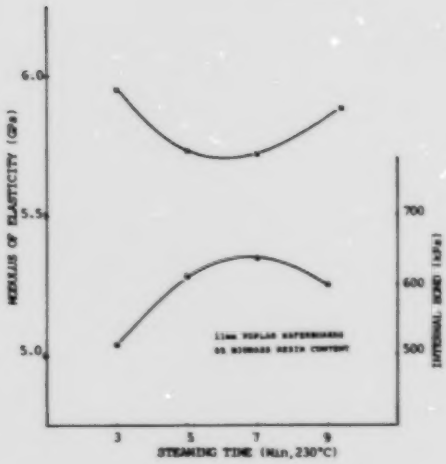
U.S. Patent application describes a method of extracting liquid thermosetting resin from lignocellulosic material. This method involves a pretreating of lignocellulosic material of woody or non-woody nature with high pressure steam to cause a thermochemical conversion of the hemicellulose and lignin portion of the lignocellulosic material. The thermohydrolysis causes the hemicellulose to decompose mainly into low molecular weight water soluble carbohydrates. These water solubles can be extracted from the treated lignocellulosic material and concentrated by evaporation to a liquid resin adhesive of thermosetting nature which can be used for bonding wood composite panel products of exterior grade.

THE PROCESS

Figure 1 illustrates the process flow diagram which shows operational steps in sequence from initial raw material handling to final resin production.

close relationship between temperature and time was basically straightforward and in reverse order. The higher the steam temperature, the shorter the steam time and vice versa.

FIG. 3 BENDING & INTERNAL BOND STRENGTH Vs STEAM TIME (SOFTWOOD BIOMASS RESIN)



The Effect of Wood Species

Both polar and a mixture spruce and pine wood yielded good quality biomass resins which in turn produced poplar waferboards of very similar physical properties. Table 1 lists physical properties of waferboards bonded with two biomass resins fabricated under the same press conditions. It seems that biomass resins derived from both hardwood and soft wood yielded waferboard of very similar physical properties.

TABLE 1

PHYSICAL PROPERTIES OF POPLAR WAFERBOARDS (11.1 mm) USING BIOMASS RESIN EXTRACTED FROM HARDWOOD AND SOFTWOOD

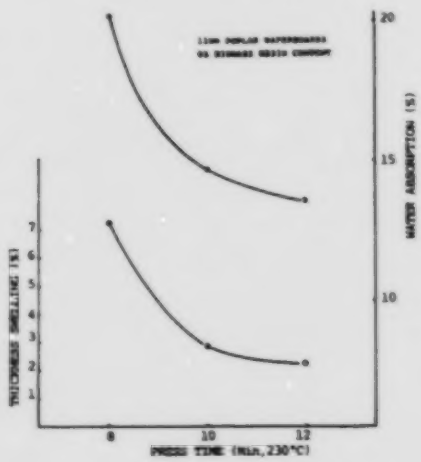
TREATMENT	DENSITY (kg/m³)	MOR (MPa) DRY	MOR (MPa) BOILED	MOE (GPa)	I.B (kPa)	THICKNESS SWELLING 24 HR SOAK %
SOFTWOOD (345 Deg C/2 min)	634	21.9	11.3	5.48	349	2.3
HARDWOOD (345 Deg C/2 min)	670	25.4	11.8	6.15	619	2.3
CAN 3-0437.0-M85		17.2	8.6	3.10	345	25

The Effect of Press Condition

Press conditions played a very important part in influencing overall waferboard properties, particularly with regard to wet strength (bending strength after 2 hour boiling treatment).

Figure 4 illustrates typically the influence of press condition upon waferboard properties. Higher press temperature or longer press time, or the combination of both always resulted in waferboard with overall improved properties. Internal bond, wet bending strength and thickness swelling were the properties most affected by the press conditions.

FIG.4 THICKNESS SWELLING & WATER ABSORPTION Vs PRESS TIME (SOFTWOOD BIOMASS RESIN)



Estimated Cost of Biomass Resin Production

The major cost for the production of liquid biomass resin is the thermoenergy required for the thermochemical conversion of lignocellulosic material and for evaporation of the liquid solution. It is estimated that about 25 MM BTU is required to process one ton solids liquid biomass resin.

The capital investment for the biomass resin production is relatively low in view of equipment and machinery required which can be readily manufactured.

An estimated cost for production of liquid biomass resin is about $100-200 per ton solid resin. The difference is mainly dependent on the cost of generating steam required for thermochemical conversion and evaporation. It is estimated that about 3 MM BTU is required to process one ton solids liquid biomass resin. The total cost of producing liquid biomass resin is estimated between 100-200 per ton solids.

FIG. 1 PROCESS FLOW DIAGRAM

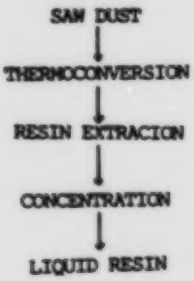
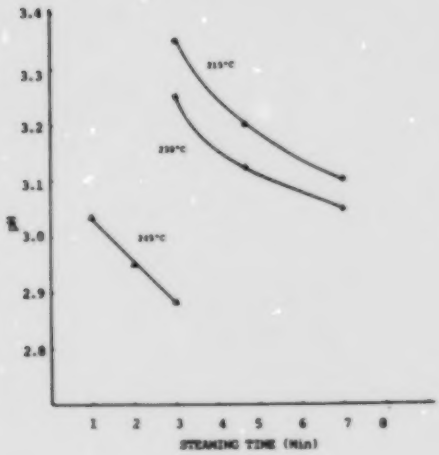


FIG.2 pH OF BIOMASS RESIN(SOFTWOOD) IN RELATION TO DEGREE OF CHEMICAL CONVERSION



MATERIAL AND METHOD

Fresh polar chips or saw dusts and a dry saw mill residue mixture of spruce and pine were obtained respectively from different sources in Ontario and Quebec for the production of resin adhesive. Poplar wafers were prepared at Forintek Laboratory using fresh poplar logs purchased from Killaloe Area in Ontario for the fabrication of waferboards.

LIQUID RESIN PRODUCTION

Green poplar chips, or a mixture of dry particles of spruce and pine saw mill residue were first loosely packed into a metal basket and the basket was then loaded into a pressure vessel. After sealing the pressure vessel, high pressure saturated steam was introduced at a predetermined pressure and for a predetermined time. At the end of steaming, the steam pressure within the pressure vessel was released gradually to atmospheric condition before the metal basket was extracted. The steam treated lignocellulosic material was hot and wet, with a dark brown colour. This raw material was washed with water and squeezed under pressure to collect liquid which contained water solubles from the decomposition and hydrolyzation of hemicellulose. The liquid resin collected from the lignocellulosic material was also dark brown in colour, with a pH of about 2.9 to 3.4, depending on the severity of steam treatment, or the degree of thermohydrolysis (Fig. 2).

The liquid resin was evaporated under vacuum to a solids content of about 50% and ready for use.

BOARD FABRICATION AND TESTING

Dried wafers (1 1/2" length, 1/4 to 1 " in width and 0.028" thick) were first sprayed with 6% liquid resin solids and formed into a mat of 18" x 18" (45.7 x 45.7 cm). The spray of molten slack wax, which is a standard procedure in commercial production of waferboard, was eliminated. The mat contained about 3-5% moisture content after resin spray. The mat was hot pressed to a panelboard of 11.1 mm thickness in a hydraulic press with heated platens of 230 degrees Celsius. The closing pressure of the press was 500psi or 35 kg/cm^2. The press times varied from 8 to 12 minutes. After pressing, waferboards were conditioned at 20 degrees Celsius and 65% R.H. to equilibrium and then cut for physical testing. CSA.3 0188-M82 standard test method was used.

RESULTS AND DISCUSSION

The Effect of Thermohydrolysis

Figure 3 shows the effect of the degree of thermohydrolysis on the bonding quality of biomass resin produced. There were optimal conditions by which biomass resin can be produced. Over or under treatment of thermohydrolysis both tended to produce an inferior biomass resin which was slow to cure, and produced a weak bond, resulting in an inferior waferboard. These optimal conditions were a combination of steam temperature and treating time. Within the steam temperatures ranging from 215 to 245 degrees Celsius, biomass resin of similar properties can be produced with a proper selection of treating time. The

THE PRODUCTION OF SUPERWAFERBOARDS

Table 2 illustrates the effect of high resin content in combination with thin wafers. Superwaferboards with physical properties approaching softwood sheathing grade plywood can be made with 9% of biomass resin solids. The superwaferboards had a bending stiffness of MOE about one million psi, and a thickness swelling, after 24 hours water soaking, of about 2%.

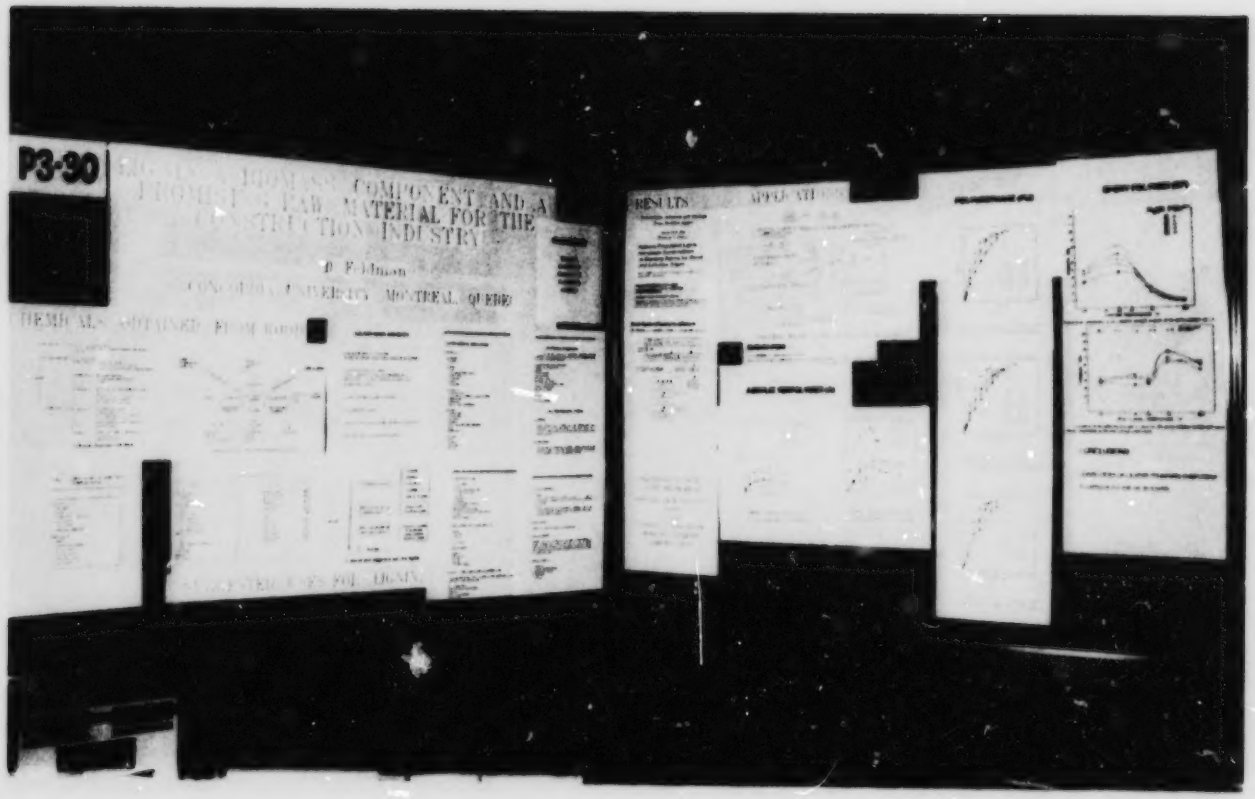
TABLE 2

PHYSICAL PROPERTIES OF POPLAR WAFERBOARDS (11.1 mm)
USING BIOMASS RESIN EXTRACTED FROM POPLAR SAW DUST AND CHIPS

TREATMENT	DENSITY (kg/m^3)	MOR (MPa) DRY	MOR (MPa) BOILED	MOE (GPa)	I.B (kPa)	THICKNESS SWELLING 24 HR SOAK %
POPLAR SAWDUST (245 Deg C/2 min)	670	24.5	10.6	6.07	583	2.4
POPLAR CHIPS (245 Deg C/2 min	663	21.9	6.5	6.12	565	2.6
CAN 3-O437.0-M85		17.2	8.6	3.10	345	25

CONCLUSION

The biomass resin system is a technological, economical and ecological breakthrough. The renewable nature, low production costs and the accessibility of on site production make this biomass resin system attractive for commercial exploitation and for wood panelboard manufacturers in particular.


P3-90
COMPONENT AND A
MATERIAL FOR THE
INDUSTRY
RESULTS

LIGNIN A BIOMASS COMPONENT AND A PROMISING RAW MATERIAL FOR THE CONSTRUCTION INDUSTRY

D. FELDMAN

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Lignin in a renewable, nontoxic, commercially available and low costing resource which has the potential of being utilized as a basic raw material for different industries. In spite of the many years of development effort however, this potential has not been fully realized. Crude oil prices and the high energy intensity necessary in the production of synthetic polymers favors the use of lignin and of its derivatives such a lignosulphonates, Kraft lignin, organosolv-lignin, steam explosion lignin, acid hydrolysis lignin, etc, in materials applications rather than the production of energy. Lignin the phenolic polymer matrix in which cellulose fibers are embedded in wood, is obviously designed as a high impact strength, thermally resistant thermoset polymer.
Some lignin derivatives are already used or are in advanced study as components of basic construction materials like concrete, mortar, wallboard, adhesives, sealants, coatings, etc.
In concrete, lignosulphonates may act as an air-entraining agent to enhance its durability, as a water-reducing additive, as a retardant of hydration, or after a certain modification, as a superplasticiser.
Lignin and some of its derivatives look as promising partners in polyblends used as adhesives, coatings, or sealants. For this reason, research on lignin-polymer systems is of continued importance in the areas of lignin-phenol-formaldehyde, lignin-acrylics, lignin-epoxy, lignin-polyorgano-siloxane, lignin urea formaldehyde, lignin-polyurethane, etc.

La lignine et une ressource renouvelable, non toxique, vendue commercialement et peu coûteuse, qui pourrait être utilisée comme matériel brut de base par différentes industries. Malgré de nombreuses années consacrées à des travaux de développement, ce potentiel n'a pas encore été pleinement réalisé. Les prix du pétrole brut et la forte énergie nécessaire à la production de polymères synthétiques favorisent l'utilisation de la lignine et de ses dérivés comme les lignosulfonates, la lignine kraft, l'Organosolv-lignine, la lignine obtenue par explosion à la vapeur, la lignine obtenue par hydrolyse acide, etc., en tant que matériaux plutôt que pour la production d'énergie. La lignine, la matrice de polymère phénolique dans laquelle les fibres de cellulose sont incorporées dans du bois, est manifestement conçue en tant que polymère thermorésistant, thermodurci, hautement résistant aux chocs.
Certains dérivés de la lignine sont déjà utilisés ou font l'objet d'études avancées en tant que constituants de matériaux de construction de base comme le béton, le mortier, les panneaux de revêtement, les adhésifs, les agents d'étanchéité, les revêtements, etc.
Dans le béton, les lignosulfonates peuvent agir en tant qu'entraîneur d'air, améliorant ainsi la durabilité du béton, en tant que plastifiant-réducteur d'eau, pour retarder l'hydratation, ou après une certaine modification, en tant que superplastifiant.
La lignine ainsi certains de ses dérivés semblent être des éléments prometteurs pour les polymélanges utilisés comme adhésifs, revêtements ou agents d'étanchéité. Pour cette raison, la recherche portant sur les système lignine-polymère (lignine-phénol-formaldéhyde, lignine-acrylique, lignine-époxy, lignine-polyorgano-siloxane, lignine-urée-formaldéhyde, lignine-polyuréthane, etc.) continue d'être importante.

I. INTRODUCTION

The studies done on the utilization of lignin are among the most challenging and promising in the area of natural polymers. Lignin is, besides cellulose, one of the principal consituents of wood.

A unique property of lignin is that it is very stable in nature and acts as a stabilizer towards various stresses to which the plant is subjected, e.g. as experienced by the inhibiting effect of lignin on the rate of enzymatic hydrolysis of wood. Flakehag [1] describes some of the functions or purposes of lignin in plants in the following manner:

(1) energy (potential and entropic) storage system;
(2) response to mechanical streses as a composite materials component;
(3) response to biochemical stresses by inhibiting enzymatic degradation of other components and low biodegradation susceptibility of the lignin itself;
(4) response to physical-chemical stresses by controlling water balances and plant response to humidity;
(5) response to chemical stressses by inhibiting atmospheric degradation and functioning as an antioxidant, a UV absorber and possibly also a flame retardant;
(6) contribution to soil properties during natural decay;
(7) purposeful interactions with other systems, including the meeting of human needs, the role in digestive systems in mammals, etc.

One important attribute of lignin emphasized by the author [1] and as yet not sufficiently taken into account is the fact that lignin is responsible for the storage of almots 40% of the solar energy bound in wood and is at a high enthalpic level as compared to many other wood or biomass components.

In this paper, some recent research contributions to the application of lignin derivatives in materials for construction will be discussed.

II. ADMIXTURE FOR CONCRETE

A. Water Reducer

A water reducer can be defined as an admixture that reduces the amount of mixing water of concrete for a given workability.

It improves the properties of hardened concrete and increases strength and durability.

Commercial lignosulfonate used in admixture formulations are predominately calcium and sodium based lignosulfonates [2].

Typical analyses of lignosulphonate-bases water reducing admixture [2]
(Spruce Wood)

	Ca-lignosulfonate %	Na-lignosulfonate %
Solid Content	54	30
Ash	6.6	--
Sulfated ash	10.9	--
CaO (in ash)	44.0	0.1
Reducing sugar	5.8	0.9
Total Sulphur	3.2	2.6

B. Superplasticizers and Air Entraining Agents

Superplasticizers belong to a new class of water reducers chemically different from the normal water reducers and capable of reducing water contents by about 30%. The admixture belonging to this class are variously known as superplasticizers, superfluidizers, water reducers or high range water reducers. They were first introduced in Japan and later in Germany.

Modified lignosulphonates is one of the main superplasticizer. The advantages derived by the use of superplasticizers include production of concrete having high workability for easy placement and production of high strength concrete with normal workability but with a lower water content. A mix having a combination of better than normal workability and lower than normal amount of water, or that less cement but having the normal strength and workability are other possible advantages.

Many lignosulfonates and, in particular, the less pure types, entrain a small proportion of air into the concrete, as the air-entraining admixtures for the concrete. When they are added to the concrete mix, entraining a controlled quantity of air in uniformly dispersed microscopic bubbles. It gives the concrete good durability, cohesion and low density.

III. MAIN COMPONENT IN POLYMER FORMULATIONS

A. Virginia Polytechnic Institute & State University, U.S.A.

W.G. Glasser [3-15], professor of wood chemistry at Virginia Polytechnic Institute & State University, project sizable new markets for lignin in such areas as adhesives, thermosetting plastics, structural foams, coating, and films. Moreover, such markets should greatly

enhance the overall economics of biomass conversion. It would enable use of an integrated two-product process, producing lignin as well as sugars that can be fermented to ethanol and other liquid fuels.

W.G. Glasser and his co-workers outlined some of their work in a series of 15 papers [3-15] under the overall title "Engineering Plastics from Lignin". Their work was sponsored primarily by the National Science Foundation, with several shortterm projects funded by the Department of Agriculture's Ethanol Program, Tennessee Valley Authority's Regional Biomass Program, the Solar Energy Research Institute, and the Robert, J. Kennedy Fund.

He has focused particularly on possible use of lignin as a component in engineering plastics. Lignin - the phenolic polymer matrix in wood in which cellulose fibers are embeded - is obviously "designed" as a high-impact-strength, thermally resistant thermoset polymer.

B. Forintek Canada Corporation, Canada

With federal support, Forintek Canada Corp. has evaluated the use of byproduct lignin in adhesives for wood composite products [16]. Tests showed that a lignin-based adhesive developed by Iotech worked effectively in waferboard, although the required pressing time was longer than for traditional composites using phenolic resins. It has been projected that two of the three full-scale wood-to-ethanol plants would produce enough byproduct lignin to meet most of the North American demand for composite board adhesive.

Lignin obtained from steam-treated wood differs substantially from kraft lignin obtained as a pulping byproduct. Characterization studies carried out at Forintek have shown that lignin from steam- treated woods can be more readily fractionated into more uniform streams and that many of these lignins are highly reactive [17].

C. Hokkaido University, Japan

Yoshihiro Sano and his coworkers [18] have investigated the utilization of lignin in resorcinol resins. High-molecular-weight solvolysis lignin (B-CWL-1) and low-molecular-weight solvolysis lignin (B-CWL-2) were isolated in yields of 14.8 and 12.3%, respectively, from spent liquor which was prepared in the cooking of beech wood with cresols and water (7:3) including a small amount of acetic acid for 2 h at 170°. The pulp was obtained with 7.3% Klasson lignin. B-CWL-1 with Mw 3500 (by GPC) and B-CWL-2 with less than 700 of molecular weight contained 0.43 of condensed cresols, respectively, 0.55 and 0.34 of phenolic OH, respectively, and 1.10 and 0.46 of alcohol OH/C_9, respectively. Three different approaches were tried in preparing lignin-based resorcinol resin adhesives. Adhesive-1 was a mixture of lignin-based phenol resin (LPF) and resorcinol. LPF was made by condensing B-CWL-1 and phenol (9:1) with HCHO. Adhesive-2 was a mixture of resorcinol resin (RF) and an aqueous NaOH solution of B-CWL-1 or 2. RF was prepared by the usual method using resorcinol and HCHO. Adhesive-3 was a mixture of RF and lignin-based resin (LF). LF was prepared by reacting B-CWL-1 or 2 with HCHO. Paraformaldehyde and a filler were added to each of the adhesives for use in marking 3-ply plywood panels. Adhesive-3 was the best of the lignin-based resorcinol resins. Tensile shear strength tests showed that as much as 80% of the resorcinol resins could be replaced by B-CWL-1, and also as much as 60% could be raplaced by B-CWL-2. With adhesive-2 being more convenient, more than 60% of the resorcinol resins could be replaced by B-CWL-1.

Utilization in phenolic resins is also studied in terms of solvolysis lignins from oak wood and beech wood isolated by solvolysis pulping with a resin can be replaced by each lignin. If necessary, each of the lignins can be condensed with HCHO in order to produce phenolic-type resins, and also the temperature of the press for the preparation of the tested plywood can be lowered for 140 to 120°.

D. Catholic University of Chile

The utilization of lignin from Pinus radiata black liquor, as a copolymer in lignin-phenol-formaldehyde resin binders was studied by Dr. M. Olivares and his coworkers. Methylolation, demethylation and ultrafiltration separation of high molecular-weight fractions were carried out in order to increase lignin reactivity. The different lignin-phenolformaldehyde resin binders mechanical properties and water resistance were evaluated through testing particleboard panels manufactured with the resins obtained. The best resin was composed of 18.8% ultrafiltered high molecular weight lignin, 22.9% phenol and 58.3% formaldehyde and had comparable properties with typical commercial resins prepared only with phenol and formaldehyde. An economic analysis was made in order to compare possible benefits obtained through the replacement of phenol by lignin products. The ultrafiltered lignin copolymer was significantly less costly than a phenol-formaldehyde resin and had comparable physical and chemical properties. [19]

E. Tentative Research done at the Centre for Building Studies

Taking in account the chemical structure and properties of lignin, preliminary studies regarding the effects of this polymeric material on the properties of the following adhesives and sealants used in Canadian construction industry were done:

- acrylic sealant
- polyurethane sealant
- poly(dimethyl-siloxane) based sealant

- epoxy adhesive

Besides the synthesis of new polymers, present efforts are focused on multiphase systems such as graft and block copolymers, composites, interpenetrating networks or by a, more simple route, that of polyblending. This last method was applied in our studies done on the above synthetic polymers.

a) Lignin-acrylic sealant polyblend

Polyblends made of acrylic sealant and Kraft lignin, in amounts up to 20 parts by weight of lignin were studied by differential scanning calorimetry (DSC) and infrared spectroscopy. The mechanical performance of the blends was established based on the adhesive or cohesive strength of the sealant adhered to different substrates such as: aluminum, Portland cement mortar and California redwood; the specimens were kept in laboratory conditions, or exposed to artificial or natural weathering. While differential scanning calorimetry proves the incompatibility between the copolymer of the acrylic sealant and lignin, infrared spectroscopy shows that there is no interaction between the polymers in this polyblend system. The improvements of the mechanical properties of the polyblends are due to the inclusion of lignin in the acrylic sealant. Lignin acts as a reinforcing filler which stiffens the sealant sufficiently to progressively increase its mechanical properties up to a point at which adhesive failure is predominant. It has also been shown that lignin may, in certain instances, increase the durability of the base sealant. [20]

b) Lignin-polyurethane based sealant

An investigation was conducted to establish the viability of blending Kraft lignin (L), with polyurethane (PU) based sealants. The sealants were tested in a detailed program where lignin-sealant blends, having blend ratios varying between 0 and 20 pbw L, were prepared on substrates of aluminium, mortar, and wood, and subjected to laboratory control (C), artificial weathering (AW), and natural weathering (NW) conditions. Results of tension testing showed that generally, lignin acts as a reinforcing agent which adds rigidity to the polymeric matrix, as indicated by the increase in toughness and modulus of blended sealants with the addition of lignin. In addition, the curing mode of PU, as determined by sequence hardness testing, was modified with the addition of lignin [21].

The morphology of blended PU sealant was studied by light microscopy (LM), scanning electron mocroscopy (SEM) and DSC. The PU was modified by the addition of various amounts of L followed by mechanical mixing to achieve a homogeneous blend. Results obtained from LM and SEM analysis reveal an even distribution of L particles in the PU matrix. Furthermore, the SEM photomicrographs clearly emphasize the differing morphologies of the constituent phases. They also depict the differences in surface texture between control and aged specimens. It is also observed that L particles tend to coalesce around the edge of voids and craters present in the PU matrix. It may be that CO_2 gas, released when the sample is exposed to moisture in the air, is more easily expelled in areas where L particles agglomerate but the reason for this is not immediately apparent. DSC shows that the two phases are immiscible which is in agreement with observations by microscopy.

c) Lignin-PVC-Poly(dimethyl-siloxane) based sealant

An adhesive sealant with improved mechanical properties has been prepared by blending a sealant based on poly (dimethyl-siloxane) - (PDS) with poly (vinyl chloride)-(PVC) and L. During this study, California redwood was used as substrate. Two commercial primers were also used to examine their effects on the adhesion of joints. By adding a small amount of L, the modulus of the sealant based on PDS+10%PVC is improved. The application of primers to the wood substrate has significantly improved the adhesion of PDS, PDS + 10%PVC and PDS+10%PVC+L polyblends. Improvement in adhesion increased the stress-strain values of the joints. Statistical inference of the experimental results are also discussed. [22]

d) Lignin - Epoxy polyblends

A lisphenol-A based epoxy polymer (EP) adhesive was modified by polyblending with Kraft lignin. L, with amounts between 10 and 20% by weight, improved the adhesive tensile strength of the epoxy polymer system. However, polyblending with 5-20% L had little effect on the adhesive shear strength (by tension loading) or the weatherability of the epoxy system. A significant improvement of the adhesive strength in shear of both the epoxy systems and the epoxy-lignin polyblends was produced after a post-curing process (4 h at 75°C). The temperature dependence of the polyblends' adhesive joint strength is typical of EP adhesives. DSC, dynamic mechanical analysis (DMA) and IR analysis were performed. At about 30°C the tensile storage modulus of EP does not change in the presence of lignin in amounts up to 20% by weight. All these showed that L is miscible with EP and it does not affect the crosslinking at room temperature. IR spectra led to similar conclusions. The gradual decrease of the peak values of tanδ

with the amount of L in polyblends is due to an increase in the tensile storage modulus and a decrease of the tensile loss modulus at temperatures close to Tg. This fact is explained by a stronger bond between EP and L, which could be formed at higher temperatures. The DSC and DMA data are in agreement with the mechanical properties of EP-L polyblends, which were reported previously.

DSC has been used to investigate the effect of L on the crosslinking kinetics of epoxy prepolymer cured with an aliphatic polyamine. L presence does not significantly affect the overall reaction order, but the activation energy increases and the slowing of the overall curing process wiht lignin content could be explained by the interaction between lignin and the polyamine hardener. The possibility of having a "false compensation" in the case of the use of single DSC scans is also discussed. [23-25]

IV. CONCLUSIONS

The author of this paper associates himself with those researchers who are confident in the future development and utilization of lignin for a diverse variety of potential applications.

Lignin degradation (hydrolysis, thioacidolysis, pyrolysis, etc.) products are used in the production of chemicals, and its use as a macromolecular compound in different polymeric systmes is of increasing importance.

Progress has already been made in a few fields such as lignin graftcopolymers, lignin thermosetting polymers and lignin-elastomer blends and continued research in these areas will no doubt yield an increased demand for lignin and lignin products in the future.

Although the present availability of technical lignins is far in excess of the demand, the potential of lignin, a nontoxic, renewable, commercially available resource to replace expensive petrochemical products is a basic incentive for revewed efforts for research in this area.

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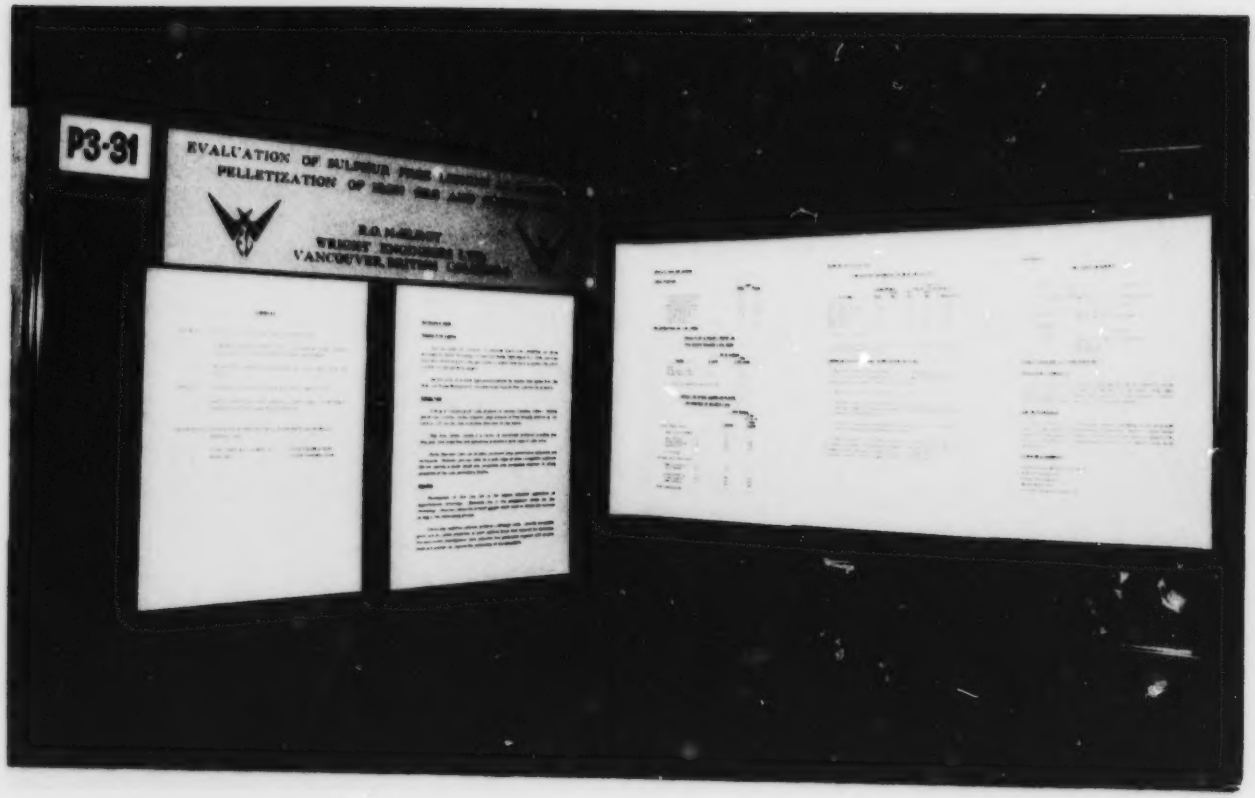
P3-31
EVALUATION OF SULPHUR
PELLETIZATION OF
WRIGHT ENGINEERS LTD.
VANCOUVER, BRITISH

EVALUATION OF SULPHUR FREE LIGNINS AS BINDERS FOR PELLETIZATION OF IRON ORE AND COKING COAL

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Sulphur free lignins produced by Staketech and Repap are potentially useful as binders in agglomeration of fine mineral products such as iron ore and coking coal. Properties of interest for these applications include low sulphur and mineral contents, solubility as a function of pH and adhesive strength. For iron ore, "green" strength of pellets is a critical parameter; preliminary results indicate satisfactory values can be obtained with lignin displacing bentonite clay. For metallurgical coal, binder acceptability requires minimal effect on coking properties. Results of pelletization tests with lignin and control binders are presented, with an analysis of potential for economic use of these biomass derived materials in selected mineral industries.

Les lignines exemptes de soufre produites par Staketech et Repap sont potentiellement utiles en tant liants pour l'agglomeration de produits mineraux fins, comme le minerai de fer et le charbon cokefiant. Parmi les proprietes d'interet pour ces applications, on compte la faible teneur en soufre et en mineraux, la solubilite en fonction du pH et l'adherence. Dans le cas du minerai de fer, la resistance "verte" des pellets constitue un parametre tres important; selon les resultats preliminaires, on peut obtenir des valeurs satisfaisantes lorsque la lignine remplace l'argile a bentonite. Dans le cas du coke metallurgique, le liant, pour entre acceptable, ne doit guere modifier les proprietes de cokefaction. On presente les resultats des essais de pelletisation realises avec de la lignine et avec des liants temoins, et on analyse les possibilities economiques de ces produits derives de la biomasse, dans certaines industries mineraux.

INTRODUCTION

Sulphur Free Lignins

New processes for recovery of cellulose (fibre) from woodchips are being developed by Stake Technology Limited and Repap Technologies Inc. Both processes have been tested at pilot scale, and produce a sulphur-free lignin by-product for which commercial uses are being sought.

Very briefly, the Stake process technology includes: steam treatment at elevated temperature and pressure, followed by rapid decompression/cooling. The Repap process technology involves digestion in liquor containing alcohol and dilute alkali. In both processes, solubilized lignin is separated from the pulp and recovered by acidification/liquid-solid separation and drying.

Conceptually, both processes may allow lower cost recovery of lignin solids than conventional Kraft or sulphite pulping, because lignin dissolved in the pulping process is precipitated by acidification so the amount of water evaporation to generate a dry product is much less than for recovery of soluble lignin from conventional processing.

Identification of suitable applications/markets for sulphur-free lignins from the Stake and Repap developmental processes could improve their commercial prospects.

This report presents results of preliminary evaluations of sulphur-free lignins as binders for coking coal and iron ore.

Coking Coal

Coking or "metallurgical" coals produced by western Canadian mines in Alberta and British Columbia contain relatively large amounts of fines (broadly defined as -100 mesh or -150 microns) due to tectonic alteration of coal seams.

High fines content results in a variety of operational problems including dust loss, poor flow properties, and operational problems in some types of coke ovens.

Pelletization is a potentially attractive method of avoiding these problems. "Pellets" (roughly spherical agglomerates formed by mixing of fine granular solids with a controlled amount of fluid) behave as large granules and, with a suitable binder, could reduce or prevent most of the problems associated with handling and shipment of the fine fraction of western coals.

Rocky Mountain coals can be easily pelletized using conventional equipment and techniques. However, previous tests on a wide range of water-compatible materials did not identify a binder which was compatible with acceptable retention of coking properties of the coal, particularly fluidity.

Petroleum, or "oil" binders are generally compatible with retention of coking properties, and may actually enhance coking behaviour. However, there are major problems associated with use of "oil" binders for wet coal as it is produced from existing coal preparation plants.

Iron Ore

Pelletization of fine iron ore is the largest industrial application of agglomeration technology. Bentonite clay is the predominant binder for this technology. However, bentonite is "acid" gangue which much be fluxed and removed as slag in the steelmaking process.

Conceptually, the potential advantages of organic binders include elimination of the bentonite component of acid gangue, associated flux requirement, and melting energy costs, as well as reducing the fuel cost for induration.

Recent publications (1,2) have dealt with chemically modified cellulose products which - although costly - provide acceptable green and dry pellet properties at lower addition levels than required for bentonite. Other recent/current investigations (3,4) have indicated that particulate organics such as peat moss and sawdust can improve the reducibility of iron ore pellets.

OBJECTIVES

Briefly, the objective of the study was to perform scoping tests on pelletization of coking coal and iron ore using developmental sulphur-free lignins in order to identify potentially promising applications for these materials.

MATERIALS AND METHODS

Lignin samples for this study were provided by Stake Technology Ltd. and Repap Technologies Inc.; both samples were provided as dry, free-flowing powders and were used as supplied.

Coal used for pelletization testwork was provided by Westar Mining Ltd. from its Balmer Operation at Sparwood, B.C.; the sample was filter cake from the fine coal cleaning operation.

A sample of iron ore "pellet feed" was provided by the Iron Ore Company of Canada Ltd., Sept Isle, Quebec; this material was tested as supplied, and also, for control purposes, blended with a sample of bentonite clay used by IOC.

All pelletization tests were done in a laboratory batch test unit fitted with a 20 cm dia. x 30 cm drum; rotation speed and angle of inclination were adjusted on the basis of visual observation to optimize pelletization behaviour for specific mixtures.

For both coal and iron ore, "green" (moist) pellet strength was assessed by drop testing five selected uniform sized pellets from a height of 45 cm to a concrete surface, and averaging the number of drops to fracture.

Pellets were tested for abrasion resistance by placing ten selected uniform pellets in a Rotap apparatus on a 6 mesh screen and shaking for 10 minutes. Stability was measured as weight percent retained. For iron ore pellets, air dry, oven dry and indurated pellets were tested for compression strength to failure on an Instron apparatus.

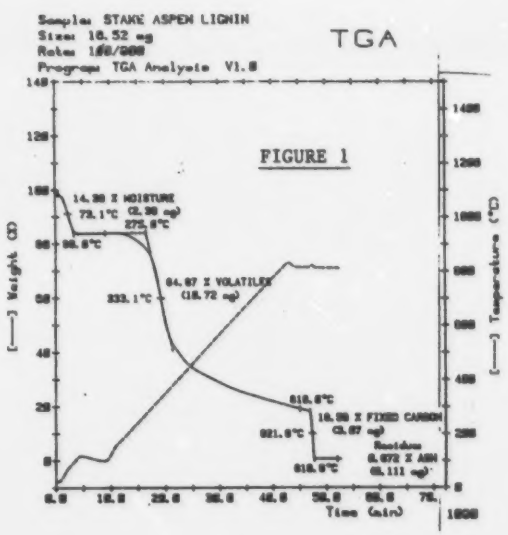
RESULTS AND DISCUSSION

Lignin Properties

The following summary of test data indicates that there are substantial differences in a wide range of properties of the two lignin materials.

	Lignin	
	Stake	Repap
Calorific value (MJ/kg, dry)	23.0	27.7
Titrable acidity to pH 9 (mEq/g, as tested)	6.9	1.0
Moisture (wt % as tested)	14.4	2.8
Fixed carbon (wt %, dry)	22.2	30.0
Carbon (wt %, dry)	56.0	65.5
Oxygen (wt %, dry)	37.8	27.9
Solubility at pH 7 (wt % as tested)	5.1	0.9

Thermal analysis behaviour of the Stake lignin is shown in Figure 1. Qualitatively, results for the Repap lignin were similar but pyrolysis onset and inflection temperatures (287 and 369°C) were higher.



In general these results appear to indicate that the Repap lignin, either during its extraction or during more extensive drying, has become a more highly condensed product; this is indicated by higher calorific value, higher carbon and fixed carbon contents, lower moisture content and lower solubility except at alkaline pH.

It is considered probable that optimization of either lignin product for use as a binder should involve evaluation of both drying conditions and extent of moisture removal. Observed differences in water solubility and film forming behaviour for filtered vs. dried samples of Stake lignin suggest that there could be major differences in adhesion properties depending on the extent and method of water removal.

PELLETIZATION OF COAL FINES

Results of Rotap stability tests on pelletized coal fines are presented in Table 1.

TABLE 1

RESULTS OF STABILITY TESTS* ON PELLETIZED BALMER COAL FINES

Binder	Wt % retained 6 mesh	Wt % retained Pan (-100 mesh)
None	3	42
Stake Lignin, 0.5%	76	12
Repap Lignin, 0.5%	62	18

* 10 g air dry pellets; Rotap 10 minutes

These data indicate that both lignin products provide significant binding, compared to a control sample of pellets prepared with water only.

Coal pellets were also prepared with both lignins using ammonia to obtain alkaline pH for maximum solubility; this had a significant effect on coking properties, so the useful test results are considered to be those with lignin binder only.

Coking Properties of Pelletized Coal

Results of free swelling index (FSI) determinations on selected pelletized coal samples indicated that the Stake lignin at 0.5 wt % addition level does not significantly affect FSI whether or not ammonia is used for partial neutralization. For the Repap lignin, a significant decrease in FSI was observed both with and without added ammonia. On this basis, further coking property tests were done on samples without binder (control), and samples with 0.5% Stake lignin. Results of fluidity and dilatometry tests are presented in Table 2.

The maximum fluidity (11 ddpm) for the control sample illustrates the very low fluidity of this coal. For the lignin treated sample, a lower maximum fluidity (6 ddpm) was observed. Considering the natural low fluidity of the coal, and the limited precision of the fluidity test at such low fluidity levels, it is considered more appropriate to regard the lost fluidity as 5 ddpm absolute rather than 50% of the maximum fluidity. Clearly, further testing would be required to confirm this.

Other fluidity test data are considered to be within the limits of precision of the test procedure.

TABLE 2

EFFECT OF STAKE LIGNIN ON PLASTIC PROPERTIES OF BALMER COAL

		Test Sample: Control	Test Sample: Coal + 0.5 wt % Stake Lignin
Gieseler Plastometer			
Max. Fluidity DDPM	11	6	
Max. Fluidity	°C	465	466
Initial Softening	°C	433	436
Solidification	°C	487	485
Fluid Range	C°	54	49
Audibert-Arnu Dilatometer			
Max. Contraction	%	25	23
Max. Dilation	%	-14	-15
Initial Softening	°C	394	403
Initial Dilation	°C	439	458
Max. Dilation	°C	480	486
Free Swelling Index		7	6.5

The principal objective of the scoping tests on coal pelletization was to identify a condition or range of conditions under which acceptable coking properties could be retained; results are considered to indicate that use of the Stake lignin would be acceptable up to 0.5 wt % in terms of retention of coking properties.

TGA data suggest a speculative explanation for the minimal effect of Stake lignin on coking properties. The lower temperature for onset of pyrolysis may allow this reaction to be effectively complete before the onset of coal fusion.

In any event, the results indicate that under identified conditions the Stake lignin product may be acceptable for use as a binder on sensitive, low fluidity coals.

Confirmation tests on a range of fine coal products, preferably including tests on samples with significantly higher natural fluidity, would be required to adequately document this conclusion. However, considering the uniformly negative results obtained in previous tests with lignin and other biomass derived binders, the present result is considered positive.

IRON ORE PELLETIZATION

Qualitatively, both lignins improved the "ballability" of the iron ore concentrate to about the same (visual) extent as bentonite.

Results of stability tests on iron ore pellets with selected binders are presented in Table 3.

In considering these results, it should be noted that the pelletization conditions in the small test drum are radically different from those prevailing in commercial sized equipment. Thus, results from this test program with various binders can be compared internally with reasonable assurance of validity, but comparisons of lab scale results with commercial practice are not realistic.

TABLE 3

COMPARATIVE PROPERTIES OF IRON ORE PELLETS

& Dosage	Green Pellets		Stability (Dry & Calcined Pellets)		
	H_2O	Drop No.	Air Dry	Oven Dry	Indurated*
None (control)	4.5	3	0.5	nil	77.2
Stake Lignin, 1% + NH_3	8.5	3-4	81.0	83.7	91.4
Repap Lignin, 1% + NH_3	8.4	3-4	60.9	78.8	90.8
Bentonite, 1%	5.7	4	69.9	78.1	96.9
Bentonite, 0.5%	5.5	4	64.6	69.5	98.8
Stake Lignin, 2%	8.5	5	87.9	83.1	77.5
Repap Lignin, 2%	8.3	8	91.4	86.6	90.9

* 10 minutes at 1100°C

With this reservation, drop shatter test results indicate marginally adequate behaviour for control pellets prepared with 0.5% and 1% bentonite (average four drops in both cases). Equivalent or better results were obtained on pellets formed with lignin only. Moisture contents of "green" pellets clearly indicate the water immobilization properties of both lignins; this property is generally regarded as a useful index of binder quality with respect to green strength. Also, drop test results are generally better at higher (i.e. as-formed) moisture contents, so results presented in Table 3 may underestimate drop stability.

Stability test results generally indicate that dry pellets prepared with lignin only had superior properties to pellets prepared with bentonite binder only. The absence of any large affect on binding properties in tests with added ammonia suggests that the acidic functional groups of the lignins may be bonding to the iron ore surfaces, thus (in affect) being neutralized in situ.

For indurated pellets, the best Rotap stabilities were observed for bentonite or bentonite lignin mixtures. This is an expected result, since the lignin is completely burned out under induration conditions and provides no residual strength. However, it is interesting to note that pellets prepared with only lignin binder were generally more stable than those containing no binder after induration and removal of the organic phase. This observation suggests that both lignins have an affect similar to that of bentonite with respect to improvement of pellet formation (i.e. compaction, spherical shape, and freedom from cracks or other defects). Results of crushing strength tests generally parallel those of the Rotap stability test.

Commercial Potential of Organic Binders for Iron Ore Pellets

Successful commercial use of organic binders for pelletization of iron ore will require a combination of low operating cost and acceptable performance in terms of pellet properties in the green, dry and indurated conditions.

Due to the preliminary nature of this study, it is necessary to make some extrapolations of the results in order to assess the commercial potential of sulphur-free lignins as binders for iron ore pellets. Results of the current study indicate:

- the green and dry condition properties of iron ore pellets prepared with sulphur-free lignin binders are generally equivalent to or better than those of pellets prepared with bentonite only, and
- properties of indurated pellets prepared with organic binders only are marginally inferior to those of pellets prepared with bentonite.

Results of a 1987 CANMET study (1), show that the strength of indurated pellets prepared with organic binder and without bentonite can be increased to ISO acceptable levels by addition of limestone to the pellet mix. This is a very important observation in relation to the general concept of using organic binders, since -instead of adding acidic (silica plus alumina) material to the pellet to obtain indurated strength - basic material is being added, which moves the overall pellet composition towards being self fluxing. This has important implications in relation to pellet reduction in a blast furnace. In effect, addition of limestone to obtain acceptable indurated pellet strength utilizes the natural components of iron ore to develop ferrite and calcium silicate (slag) bonding in the indurated pellet rather than adding extraneous acid gangue (i.e. bentonite).

The combination of current test results on low cost organic (lignin) binders and the results of CANMET investigations on organic binders with limestone addition is considered to form reasonable technical justification for further experimental work in evaluation of the two sulphur-free lignins for use in iron ore pelletization.

If acceptable pellet strength properties can be proven by further testwork, then use of organic binders has a further potential for improving iron ore pellet properties in the area of reducibility. Reports of recent studies in Canada and elsewhere (3,4) indicate that reducibility (the rate at which iron oxide reduction occurs under constant conditions of temperature and reducing gas) can be substantially improved by addition of peat moss, sawdust and other organic materials to pellet feed. Pyrolysis and combustion of these materials during pellet induration results in porosity which allows the reducing gas access to the interior of the pellet, leading to homogenous rather than topochemical reduction.

Cost Factors

The recent CANMET study investigated chemically modified celluloses and guar gum; there are also numerous reports regarding use of "PERIDUR" (a commercial cellulose derived binder). Examination of material cost data presented in Table 5 clearly indicates that such materials must be used at very low levels of addition in order to be cost-competitive with bentonite.

TABLE 3

COMPARATIVE COST DATA

FOR VARIOUS PELLET BINDERS

Binder	Delivered Cost* ($Can./tonne)	Notes
Bentonite	100	Silica and alumina require basic fluxes.
Sulphite Lignin	200	Ammonia salt, dry weight basis, fuel value approx. 50% of oil
Carboxymethyl Cellulose	2000	No residue, fuel value less than lignin on dry wt basis
Guar Gum	3000	No residue, fuel value 75-80% of oil on weight basis

* Approximate, based on Chemical Marketing Reporter, March, 1989; $(Can.)1.00 = $(U.S.)0.84

Economic assessment of lignin or other organic binders compared to bentonite is complicated by the numerous site specific considerations relating to binder use at a particular pellet producing facility. The following analysis (with noted assumptions) indicates that the direct cost of lignin binder at the same dosage as for bentonite would be approximately 50% higher. Thus, offsetting advantages (reduced acid gangue, improved reducibility, etc.) and/or lower dosages would have to be considered.

NET COSTS OF BINDERS

Lignin		
(Assumed) dlvd cost		$ 200 /tonne, dry basis
Subtract fuel equivalent cost ($2/GJ for sulphur free heat units)		$ 55 /tonne, dry basis
Net cost		$ 145 /tonne
Potential benefits	• enhanced reducibility • reduced slag volume, flux and heat	
Bentonite		
(Assumed) dlvd cost		$100/tonne
Liabilities	• transport of acid gangue to blast furnace • flux cost • melting energy • slag disposal	

CONCLUSIONS AND RECOMMENDATIONS

Pelletization of Coking Coal

Results of this study indicate that lignin derived from the Staketech pulping process can be used as a pelletizing binder for sensitive, low fluidity coking coals. Further testwork would be required to document this to a level of certainty required for coal marketing, but the present results are considered positive.

Use of pelletizing technology for coal fines will require a different approach to drying than the fluid bed technique used at most currently operating mines. For this reason, pelletization technology is more likely to be adopted by a new or expanding coking coal mining operation.

Iron Ore Pelletization

Results of this study indicate that the Staketech and Repap lignins can provide improved green pellet properties compared to bentonite. Subject to experimental confirmation that acceptable properties can be obtained with lignins at (about) 0.5%, with limestone addition for indurated strength, site specific cost-benefit studies would be appropriate.

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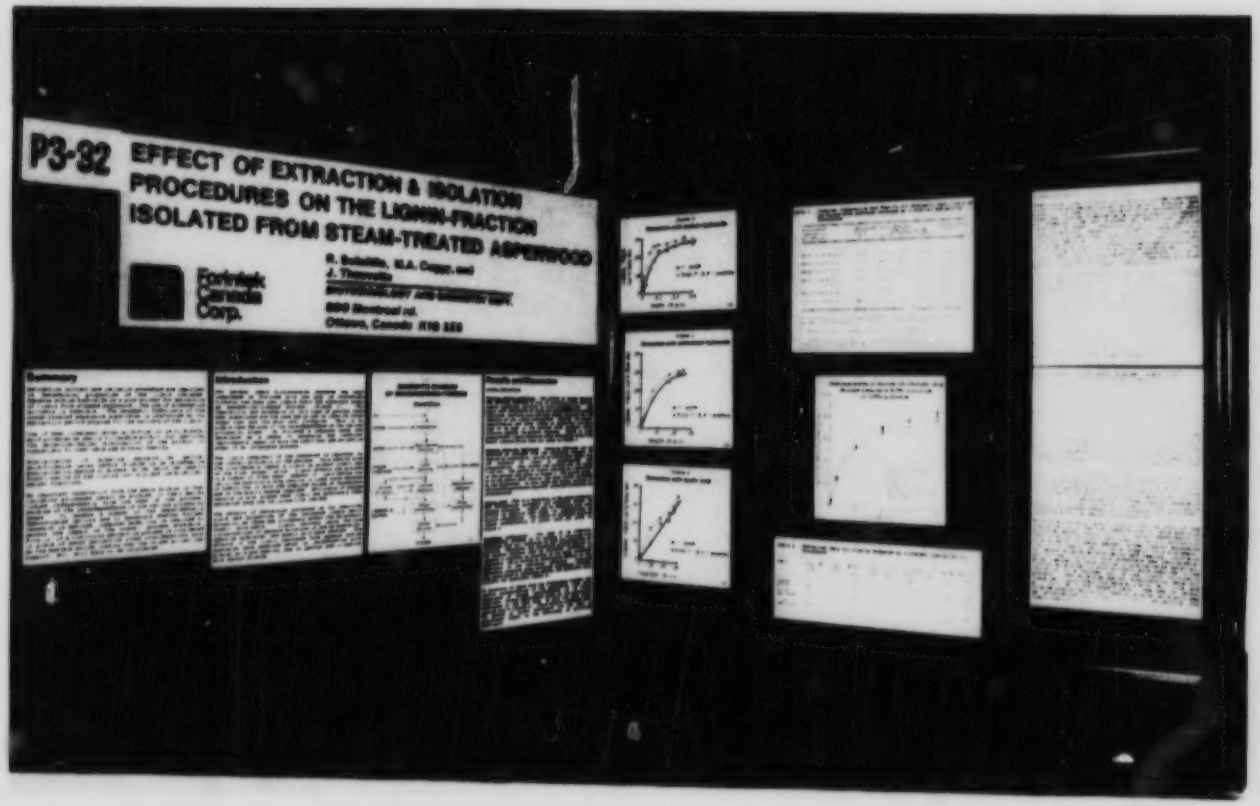
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EFFECT OF EXTRACTION & ISOLATION PROCEDURES ON THE LIGNIN-FRACTION ISOLATED FROM STEAM-TREATED ASPENWOOD
Forintek Canada Corp.

EFFECT OF EXTRACTION AND ISOLATION PROCEDURES ON THE LIGNIN-FRACTION ISOLATED FROM STEAM-TREATED ASPENWOOD

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Economic evaluation of a bioconversion process for the conversion of aspenwood residues to fuels and chemicals indicated that extraction of lignin from the pretreated substrate prior to enzymatic hydrolysis is required in order to lower both handling and capital equipment costs.
Effects of recovery processes on the resulting yield and properties of the l'gnin merit attention as these may ultimately affect the by-product credit for this component of the feedstock.
Three aqueous solvents were studied for the extraction of lignin: these were sodium hydroxide, ammonium hydroxide, and acetic acid. The effects on the lignin isolated from aqueous sodium hydroxide were also examined after (a) acidification with mineral acid and heating, and (b) partial neutralization with carbon dioxide.
Results of these studies indicate that the yields and properties of the lignin-fraction obtained depend on the recovery procedures employed. A number of extraction options are feasible. Further computer modelling is required to determine which of the extraction options considered will give the greatest cost benefit to the overall process.

Une évaluation économique d'un procédé de bioconversion des résidus de bois de tremble en combustibles et en produits chimiques a indiqué que l'extraction de la lignine à partir d'un substrat pré-traité avant l'hydrolyse enzymatique constitue une étape nécessaire pour réduire les frais de manutention et le coût des biens d'équipement.
Les effets des procédés de récupération sur le rendement et les propriétés de la lignine obtenue valent la peine d'être pris en considération car ils peuvent influer ultimement sur le crédit de produit secondaire pour cet élément de la matière de départ.
Trois solvants aqueux ont été étudiés pour l'extraction de la lignine; il s'agit de l'hydroxyde de sodium, de l'hydroxyde d'ammonium et de l'acide acétique. Les effets sur la lignine isolée à partir de solutions aqueuses d'hydroxyde de sodium ont également été étudiés après a) acidification avec acide minéral et chauffage et b) neutralisation partielle avec gaz carbonique.
Les résultats de ces études indiquent que les rendements et les propriétés de la fraction lignine obtenue dépendant de la méthode de récupération employée. Un certain nombre de méthodes d'extraction sont applicables. Une modélisation par ordinateur plus poussée est nécessaire pour déterminer quelle méthode, parmi celles qui sont considérées, sera la plus économique compte tenu du procédé global.

INTRODUCTION

For several years bioconversion research has been undertaken at Forintek with the goal of converting forestry residues into liquid fuels and chemicals using an enzymatically-based process, (Figure 1).

As research advances have been made, the feasibility and economics of this type of process have been questioned and the need has arisen to identify those steps that are the most cost intensive. This is no simple task because of the interdependence of the various processing steps. At Forintek a computer model was developed as a means of assessing how technical improvements impact on both the individual and collective steps of an integrated process.[1]

The lignin component of the feedstock is important to the overall economics of the process. This results from the considerable impact a lignin by-product credit has on the final ethanol price. Lignin affects the process in a number of other ways. Removal of lignin before the cellulose hydrolysis step results in lower costs because of reductions in both the required volume of fermenters and in the mixing energy required. Efficiency of enzyme recycle is also higher when lignin has previously been extracted from the cellulose-rich residue.

The effects of extraction processes on the resulting yield and properties of the recovered lignin merit attention as these may ultimately affect the by-product credit attainable. Lignin recovery using various concentrations of aqueous

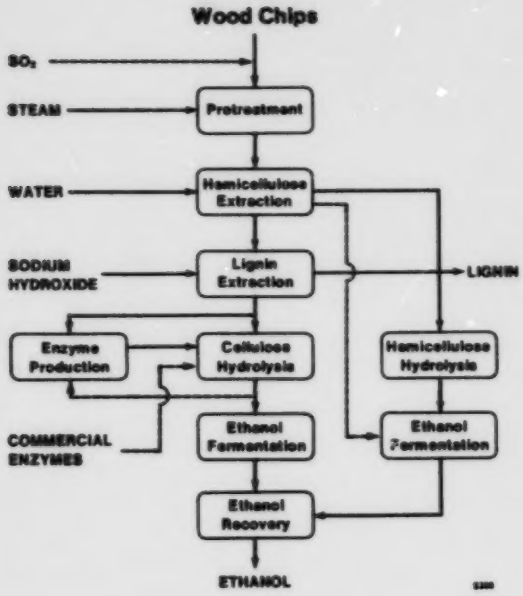

Figure 1 Schematic Diagram of Bioconversion Process

solutions of sodium hydroxide, ammonium hydroxide, and acetic acid were studied. The effects on the lignin recovered from aqueous sodium hydroxide were examined after (a) acidification with mineral acid and heating, and (b) partial neutralization with carbon dioxide.

EXPERIMENTAL

Steam treatments

Steam treatments were done in a 2-litre pressure vessel closed at both ends by pneumatically actuated ball valves. Commercial, never-dried aspenwood chips were loaded directly into the vessel and after steam treatment (240°C, 80 s) were exploded through the lower ball valve into a cyclone. The steam-treated aspenwood was extracted twice with water by stirring for two hours at a 5% consistency and then filtering through a coarse sintered glass funnel.

Lignin extraction

Water-extracted material (SHA-WI) was stirred with the solvent under investigation at room temperature for 1 hour and the resulting product filtered to remove the solid residue. The residue was then extracted and the product filtered a second time. The residue was washed with the minimum amount of water to remove the extraction solvent.

Lignin recovery

Aqueous sodium hydroxide: The alkaline extracts were acidified to pH 2.5 with hydrochloric acid and the resulting precipitate recovered by filtration or centrifugation. The solid recovered was repeatedly washed with water and the precipitated, washed lignin was subsequently air-dried. Effects of heating on the acidified extracts: The extracts were acidified with sulfuric acid and then heated to the required temperature for the stated time by passage of steam through the solution. After cooling, the lignin precipitated was recovered (if possible) by filtration. Partial neutralization with carbon dioxide: The gas was passed through the alkaline extract until the pH was lowered to 6.75-8.2. Then the precipitated lignin collected (if possible) by filtration. When required, the solution was heated as above with steam prior to recovery of precipitated lignin. Aqueous ammonium hydroxide, acetic acid: Aliquots were taken from the extracts and freeze-dried to determine the solid contents.

Analysis

Chemical analyses of lignins were performed using the procedures previously described.[2] Carbohydrate contents were determined by acid hydrolysis and HPLC analysis of the liberated sugars.

Enzymatic hydrolysis

Flasks containing the substrates at a concentration of 2% in a 0.05 M sodium acetate buffer at pH 4.8 and cellulase preparation (Novozym/Celluclast) were incubated for 3 days (27 FPU/g substrate), or 4 days (10 FPU/g substrate), at 45°C with shaking at 150 RPM. Aliquots were removed at intervals from the supernatant liquid of the enzymatic hydrolysates and analysed for released sugars by HPLC.

RESULTS & DISCUSSION

Lignin extraction

Aqueous sodium hydroxide: The method of lignin removal and recovery modelled is that of extraction with aqueous sodium hydroxide followed by acid precipitation. The major cost components of these are associated with sodium hydroxide, sulfuric acid and heat energy required for the recovery of the lignin precipitate. Ideally, the alkali concentration and total volume of extraction solvents need to be kept to the minimum level possible while ensuring maximal by-product recovery.

Yields of acid precipitable lignin recovered after extraction versus the alkali concentration used are shown in Figure 2. Lignin recovered in this manner normally has a combined Klason and acid-soluble content of 92-96% and low carbohydrate content 1-3%.

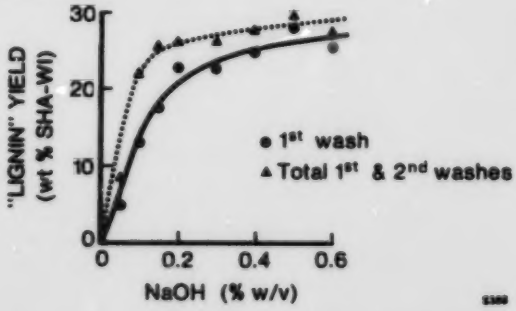

Figure 2 Extraction with Sodium Hydroxide

Caustic at 0.4% w/v has been widely used in bioconversion work to extract the lignin component after steam-treatment. As expected, a minimum concentration of alkali (0.15-2.0%) was required to achieve extraction of a substantial portion of the lignin. Once this level was reached only small increases in further recovery were achieved with increasing concentrations of aqueous alkali. The results suggest that it may be possible to use a concentration of 0.15-2.0% sodium hydroxide and retain the same solution volume. Above an alkali concentration of 0.2% w/v, the quantity of lignin recovered by the second extraction was not significantly greater than the amount assumed to be present in the solvent from the original extraction retained in the cellulosic residue. Depending on the effect on the enzymatic hydrolysis of any alkali-soluble lignin remaining after water-washing to remove the alkaline extracting solvent, one extraction step at higher alkali concentration may be more cost effective in the overall process.

Aqueous ammonium hydroxide: Ammonium hydroxide can be recycled by recovery from the extracting solution of ammonia by evaporation, giving an alternative option for the recovery of lignin to acidification and precipitation. This solvent was studied over the range 7-25% w/v. The yields of lignin isolated by evaporation of the solvent are shown in Figure 3. The yields given, as in the acetic acid results, are total solids recovered by the extraction. In both cases the lignin, because of the recovery procedures employed, contained contaminating carbohydrates.

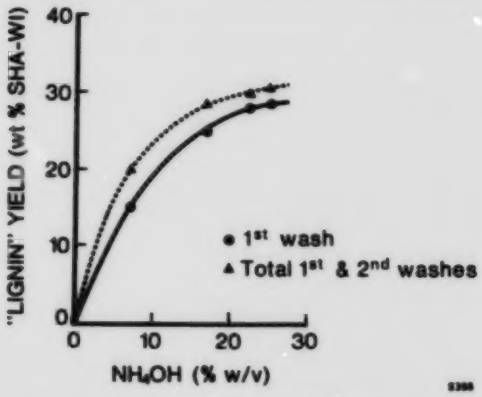

Figure 3 Extraction with Ammonium Hydroxide

The yield of material recovered increased substantially up to an ammonium hydroxide concentration of about 12.5%. As observed with sodium hydroxide, once this concentration was exceeded only incremental gains in recovery were achieved by a second extraction. High concentrations of ammonium hydroxide (>6 M) were required to achieve a degree of extraction comparable to that attained using sodium hydroxide (ca. 0.05 M). This reflects the greater basicity of sodium hydroxide solutions.

Acetic acid: This is a by-product of the steam-treatment and fermentation processes and therefore should be readily available. Lignin can be recovered from this solvent by dilution with water, or, alternatively by solvent evaporation. The yields of extracted material versus concentration of acetic acid are given in Figure 4. As the acetic acid concentration in the solvent was raised the amount of material removed from the water-washed substrate increased. This probably reflects the fact that as the percentage of acetic acid in the solvent composition is increased, the Hildebrand solubility parameter for the solvent approaches more closely the value normally assumed for maximum solubility of lignin (δ = 11).[3,4]

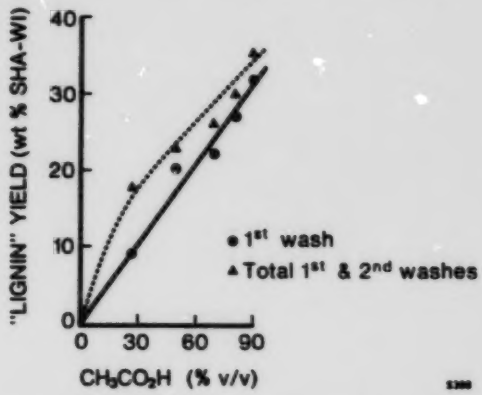

Figure 4 Extraction with Acetic Acid

Enzymatic hydrolysis: The goal of an effective pretreatment process is to produce a cellulose-rich substrate that will hydrolyse as fast and completely as possible. Therefore, any extraction process applied to the treated material must be efficient, providing as complete a recovery as possible of the major feedstock components, while having no deleterious effects on the hydrolysis of the cellulosic substrate. Selected substrates prepared using different extraction solvents were hydrolyzed to determine whether the substrates were suitable for hydrolysis (Table 1).

Table 1 Chemical Composition and Results for Enzymatic Hydrolysis of Cellulose-Rich Residues Produced by Differing Extraction Procedures

Substrate[a] (extraction procedure)	Cellulose rich residue Yield (%)[b]	Composition (%) Glucan	Xylan	Lignin	Hydrolysis Yield[c]
NaOH (0.15 % x 2)	73.8	79.3	7.6	18.9	102.9
NaOH (0.4 % x 2)	71.0	82.7	6.7	10.0	97.6
NaOH (0.6 % x 1)	73.5	77.6	6.4	10.5	100.5
NaOH (0.4 % x 2, 2.0 % x 1)	69.9	83.2	5.9	8.8	100.0
NH_4OH (24.0 % x 2)	77.0	77.4	5.7	14.3	100.4
CH_3CO_2H (88.5 % x 2)	74.5	75.0	6.0	10.9	99.8

[a] Composition of the water-washed steam exploded aspenwood: glucan, 58.9 %; xylan, 5.3 %; lignin (K+AS), 30.6 %

[b] Based on 100g OD water washed starting material

[c] Yield of glucose and glucose equivalent at 72 h from hydrolysis of substrate at 2 % with Novo enzyme at 27 FPU/g substrate

The hydrolysis profiles indicated that all the substrates examined were hydrolyzed with 90% conversion yields within 48 hours. To ascertain if there were any differences between the initial susceptibility of the substrates, they were hydrolyzed at enzyme concentrations of 10 FPU/G substrate. Within experimental error all the substrates hydrolyzed at the same rate and gave the same final glucose yields (Figure 5). These results indicated that the method of lignin extraction did not have a significant impact on the efficiency of cellulose hydrolysis.

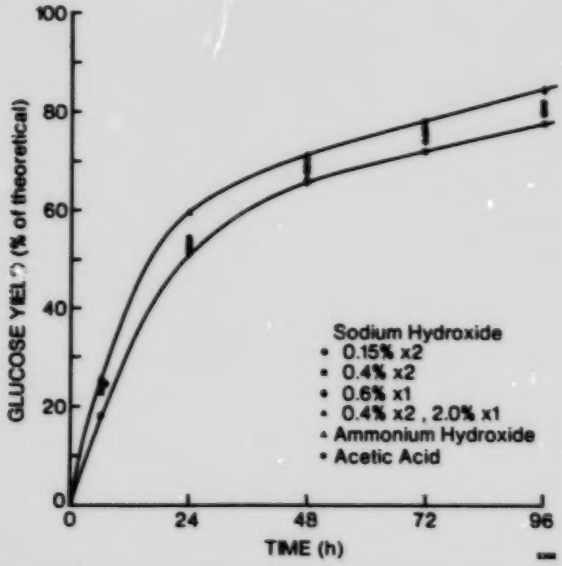

Figure 5 Hydrolysis Profiles of Cellulose-Rich Substrates using Novozym-Celluclast at 10 FPU/g substrate (12-13 FPU/g cellulose)

Lignin isolation

Previously, the effects of various steam-treatment conditions and extraction solvents (alkali, acetone, and ethanol) on the lignin isolated from aspenwood were examined.[5] Yields of extractable lignin-fractions depend on steaming time and whether an additional acidic catalyst is used. Characteristics of the isolated lignin-fractions depend on steaming catalyst and extraction solvent used. In our previous work the "standard" lignin adopted as starting material for modification reactions was extracted from the water-washed, steam-treated aspenwood by alkaline extraction (0.4% sodium hydroxide). The lignin was then precipitated by addition of acid (sulfuric or hydrochloric) to decrease the pH of the extracts from 12.5 to 2.5. Isolation was then achieved by centrifugation, followed by water-washing. As the need arose to prepare larger quantities of lignin for modification and testing in applications, the inappropriateness of this procedure for large scale operation became clear.

Heating of the acidified extracts to produce a filterable lignin product: In computer modelling of the bioconversion process, the proposed method of lignin recovery is to acidify the alkaline extracts with sulfuric acid, heat the resultant mixture and then recover the precipitated lignin by filtration. The effect of heat treatment after acidification was examined for two concentrations of sodium hydroxide extracts (0.2, 0.4%). After acidification to pH 3.5 the extracts were heated to 90°C and held at this temperature for 10 minutes. After cooling, the solutions were filtered to recover the precipitated material. In both cases the yields of precipitate were approximately 3% lower than for the unheated precipitates recovered by centrifugation, but the solids contents of supernatant solutions were correspondingly higher. The recovered lignins were substantially lighter in coloration than the materials recovered without heat treatment being medium brown instead of black in color. This observation must be considered to be an indication that if the lignin is recovered by a process involving a heating step after acidification of the alkaline extracts, then there may be an effect on the chemical characteristics of the recovered lignin.

Acidification using carbon dioxide: Black liquor from Kraft or soda pulping processes contain lignin dissolved in the phenolate form. Recovery of 40-60% of the lignin can be achieved by acidification using flue gases (carbon dioxide), whereby the phenolic groups are liberated and the lignin precipitates largely because of the salting out effect of inorganics of the black liquor. The precipitated alkali lignin can be removed by filtration at preferably elevated temperatures (60-80°C). At higher temperatures (90°C) the precipitate melts to form a viscous tar which can be mechanically separated and subsequently purified.[6,7]

Two experiments were performed using carbon dioxide to lower the pH of alkaline extracts (0.4%) of the water-washed, steam-treated aspenwood (100 g O.D. basis). In the first experiment, after the acidification the resultant precipitate (22.5 g) was recovered by centrifugation because it could not be collected efficiently by filtration. In the second, after the passage of the gas, the resultant solution was heated to 90°C. After cooling, the precipitated material was easily recovered by filtration. The material recovered in each case was very light in coloration. In subsequent larger scale experiments recovery by filtration after acidification with carbon dioxide and heating was not always achieved. Use of carbon dioxide followed by a thermal treatment is an option which merits further consideration.

Effect of alternative isolation procedures on characteristics of lignins: Lignins prepared on a larger scale for composites research were analyzed to determine if the alternative isolation methods affected their characteristics. These lignins were isolated from a single caustic extraction (0.4% w/v) of water-washed, steam-treated aspenwood (240°C, 80s). The lignin precipitated by carbon dioxide acidification had to be isolated by centrifugation as heating did not result in a filterable product. As indicated in Table 2 the only major difference between these lignin preparations is in their relative molecular-weight distributions.

The higher average molecular-weights of the mineral-acid-acidified, heat-treated and carbon dioxide, heat-treated lignin-fractions probably are the result of different mechanisms. Heat treatment at pH 2.5-3.5 after mineral acid acidification

Table 2 Analytical Data for Lignins Prepared by Different Precipitation Procedures

Sample	Klason + AS Lignin (% wt)	Sugar Content (% wt)	Methoxyl (% wt)	Hydroxyl Content Total (% wt)	Hydroxyl Content Phenolic (% wt)	Nitrobenzene Oxid[a] total v + s (% wt)	Nitrobenzene Oxid[a] ratio s/v	Mol Wt. Distribution M_w	Mol Wt. Distribution M_n
Standard acid ppt.	94.1	1.0	18.8	10.6	1.7	16.3	2.5	6459	1419
Acid ppt., heat treated	93.2	0.9	19.0	10.6	1.7	19.0	2.0	10032	1439
CO_2 ppt., heat treated	93.4	0.4	19.0	11.7	1.6	20.2	2.2	10191	1676

probably results in some condensation and polymerization of the material. Acidification with carbon dioxide results only in the precipitation of the most readily precipitable and high molecular-weight lignin fraction. Recent experiments in the isolation of lignin recovered by caustic extraction from a batch of water-washed, steam-treated aspenwood (542 g O.D. basis, 240°C, 100 s) support this latter statement. By carbon dioxide acidification and heating, initially 40% of the lignin in this substrate was recoverable (assuming a substrate lignin content of 30% and a Klason and acid soluble lignin content of 95% for the isolated lignin). After removal of this initially precipitated material, further acidification with sulfuric acid resulted in the isolation of a further 30% of the lignin originally present. The molecular-weight distribution data for these two lignin-fractions were M_w = 9712, M_n = 1304, and M_w = 5855, M_n = 929 respectively. The use of carbon dioxide precipitation followed by mineral acid provides an alternative to organic solvent extraction for fractionation.

CONCLUSIONS

Extraction solvent and isolation procedure are important in determining properties of the lignin isolated. Aqueous sodium hydroxide is a good solvent for extraction of lignin from steamed aspenwood. The use of alternative solvents is feasible. The enzymatic hydrolysis of the steam-treated aspenwood substrates is unaffected by the extraction method adopted for the recovery of the lignin.

Use of heat treatment after acidification using mineral acid produces an easily filterable product, but, perturbs the molecular-weight distribution of the product in comparison to that obtained without heating.

Precipitation of alkaline extracts by partial acidification using carbon dioxide is an alternative precipitation method to mineral acids, which can lead to fractionation of the lignins into high and low molecular-weight fractions.

An important observation from the above studies is that isolation processes cannot be studied, or their merits judged independently from the rest of the process, because of the interdependence of the various processing steps. To assess a number of the experimentally demonstrated options and to ascertain whether further research is merited, computer modelling is required to assess the impact on the overall process economics. Finally, if a continuous extraction process is considered in place of batch extraction other considerations such as the maximum solids loading that the chosen solvent can support, etc. will have to be considered.

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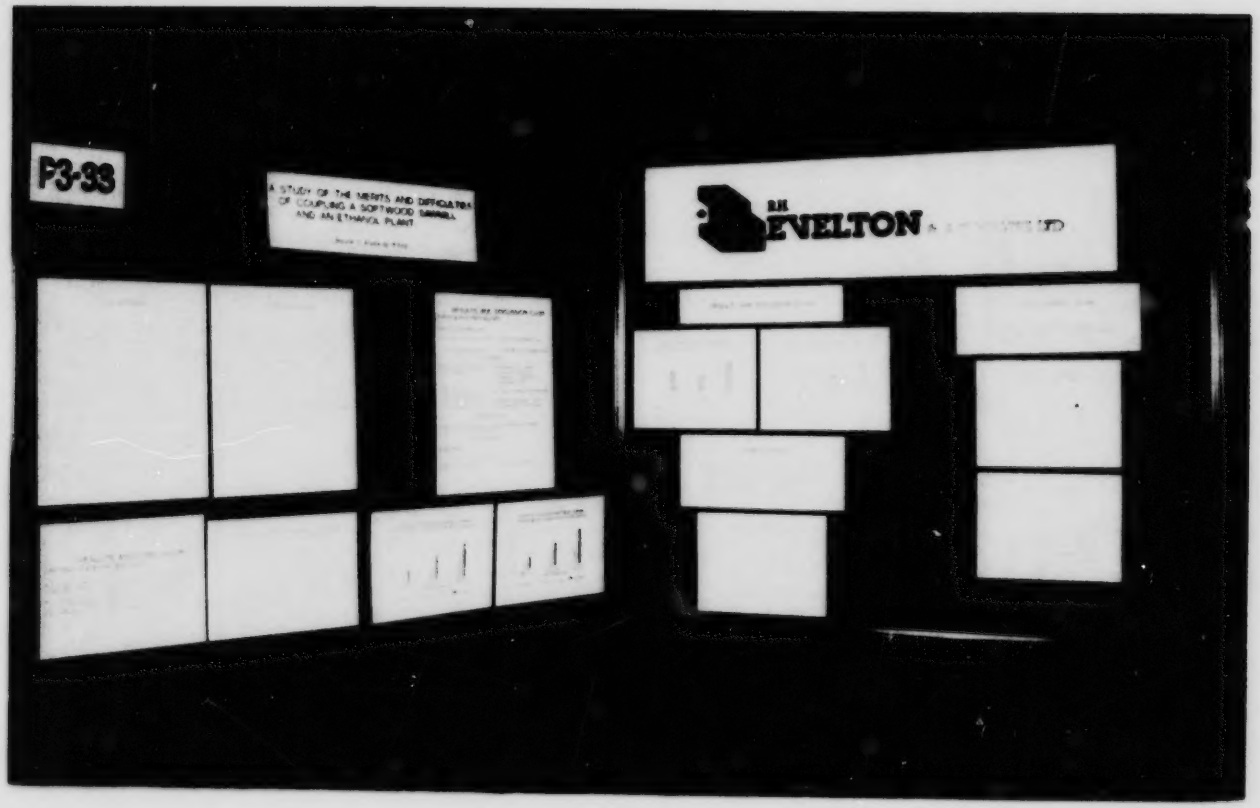
P3-93
A STUDY OF THE MERITS AND DIFFICULTIES
OF COUPLING A SOFTWOOD SAWMILL
AND AN ETHANOL PLANT
R.H.
EVELTON

A STUDY OF THE MERITS AND DIFFICULTIES OF COUPLING A SOFTWOOD SAWMILL AND AN ETHANOL PLANT

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Softwood sawmills produce quantities of wood residues in excess of that for their own energy needs. These residues could potentially be converted to ethanol for use as a fuel additive or an industrial grade product. The technical and economic feasibility of coupling an enzymatic or acid hydrolysis based ethanol plant to a softwood sawmill was investigated. Conceptual cost estimates for the ethanol plants were made using BIOSIM, a previously developed computer simulation program which facilitates preparation of material balances and cost estimates for bioenergy systems. Input was obtained from industry to determine their interest in, and concerns about, coupling a sawmill operation to an ethanol plant. Results of the discussions with industry helped to focus on the issues relevant to application of ethanol production technology in the forest industry.

Les scieries de bois de resineux produisent plus de residus de bois qu'elles n'en ont besoin pour satisfaire leurs propres besoins d'energie. Or, ces residus pourraient peut-etre convertis en ethanol pour etre utilises comme additif pour combustible ou comme produit de qualite industrielle. On a etudie la faisabilite technique et economique de l'association d'une usine ou l'ethanol est produit par un procede enzymatique ou par hydrolyse acide, a une scierie de bois de resineux. Les evaluations conceptuelles des couts des usines de production d'ethanol ont ete effectuees a l'aide de BIOSIM, un programme de simulation informatique mis au point anterieurement, qui facilite la preparation des bilans matieres et des evaluations des couts dans le cas des systemes bioenergetiques. L'industrie en nous faisant part de ses interets et de ses preoccupations, nous a aide a nous concentrer sur les questions qui touchent l'application de la technologie de la production d'ethanol a l'industrie forestiere.

INTRODUCTION

Extensive research has been done worldwide to commercialize acid and enzymatic processes for the production of ethanol from wood. The work done up to 1983 on most near commercial processes has been summarized by Levelton and Elliott (1983), including Soviet technology, the Madison process, New Zealand Forest Research Institute, Coque E Alcool da Madiera S/A (COALBRA) and others. Since 1983 further work has been done on hydrolysis of wood using hydrofluoric acid, various efforts have been made to commercialize the New Zealand Forest Research Institute (FRI) process and much progress has been made with enzymatic hydrolysis processes.

In spite of the considerable research that has been done in recent years on production of ethanol from wood feedstocks, no commercial-scale plants have been installed or are planned in North America. However, ethanol is made commercially in large quantity from agricultural feedstocks. The wood products manufacturing sector of the forest products industry could potentially utilize wood residues from sawmills to produce ethanol in small plants coupled to existing operations. Such plants could utilize residues presently being incinerated or disposed of in landfills to produce ethanol, providing an opportunity to diversify the plants markets, while reducing environmental pollution problems.

A study was undertaken to explore the potential for implementation of ethanol production processes at sawmills. BIOSIM (Edwards and Wasik, 1989) was used to simulate the material flows in ethanol plants sized to suit waste streams from sawmills and generate estimates of capital and operating costs. Industry was consulted to obtain feedback on the practical problems of installation of ethanol plants at their operations and to explore their economic and technical concerns about ethanol production processes. This aspect of the study is continuing.

RESULTS AND DISCUSSION

Sawmill Material Balance

Western interior sawmills utilizing spruce/pine/fir logs were used as a basis for the analysis. Typical yields of chips and residues for three sizes of sawmill common to the Interior of B.C. are summarized in Table 1. Lumber yield for

Table 1 Material Balance for Western Interior Softwood Sawmill

Nominal Lumber Production MMfbm/year	Solid Wood to Mill		Byproducts/Residues Generated						
			Chips		Shavings		Sawdust		Bark
	10^3m^3	10^3ODt[1]	10^3m^3	10^3ODt	10^3m^3	10^3ODt	10^3m^3	10^3ODt	10^3m^3
50	255	95.9	98	36.8	28	10.5	38	14.3	51
100	510	191.8	196	73.7	56	21.1	77	29.0	102
150	755	283.9	295	110.9	84	31.6	115	43.2	153

[1] Average wood density = 376 $ODkg/m^3$

these cases is 34.5% of mill input volume. Chips are of high value and are normally sold locally or exported for pulping. Shavings and sawdust would in some cases be sold for pulping, but most often are burnt for energy or incinerated along with bark residues.

Acid Hydrolysis

The revised Madison process tested at a pilot scale by the New Zealand Forest Research Institute was used as a basis for the analysis of the acid hydrolysis route to ethanol production from wood. The FRI process was tested extensively with Pinus Radiata. With this and similar softwoods hydrolysis proceeds by steaming wood chips at 140 - 150°C for about 30 minutes then hydrolyzing with 0.5% sulphuric acid at 150°C, rising to 190°C, for approximately 120 minutes. The produced hydrolyzate is neutralized then the hexose sugars present in the hydrolyzate are fermented to produce ethanol.

Burton (1982) gives the material balance for the FRI process. For Pinus Radiata, the ethanol yield is 20.5% of the dry weight of wood, which is equivalent to 256 L/dry tonne. In this material balance, no allowance was made for losses during fermentation and distillation. Including an allowance for these losses reduces the yield to about 240 L/dry tonne.

In previous work, the detailed material balance for the FRI hydrolysis process developed by Burton (1982) was related to the composition of Pinus Radiata to obtain yield factors that could be applied approximately to other softwoods. These were incorporated into a hydrolysis simulation module for use with other process simulation modules utilized in a Bioenergy Simulation program called BIOSIM. Using material balance relationships for all conversion steps in an acid hydrolysis based plant producing anhydrous ethanol yields annual ethanol production rates in Table 2. Three feedstock scenarios were considered for the plant: chips only; sawdust and shavings only; and chips, sawdust and shavings. The overall ethanol yield in all cases is 236 L/dry tonne. In all cases, the ethanol plants are small by world standards and production costs should be expected to be higher as a result. Whether or not chips would be utilized as a feedstock depends on the revenue which could be derived from ethanol relative to the price of pulp chips.

Capital costs for acid hydrolysis were estimated for each of the possible sawmill/feedstock combinations and included feedstock storage and handling, hydrolysis and hydrolyzate recovery, hexose fermentation, azeotropic distillation, boiler system, lignin residue dewatering, waste water treatment and other offsites (Table 2). Capital costs range from $ 2.73 to $ 1.23 per annual litre, as the plant annual output increases from 5.9 ML to 43.6 ML.

Operating and maintenance costs shown in Table 2 include electricity, transportation fuel, fermentation nutrients, acid, lime and manpower, but exclude any cost for feedstock. These costs decrease from $ 0.18/L for the smallest plant to $ 0.10/L for the largest plant.

Enzymatic Hydrolysis

Enzymatic hydrolysis is a potentially attractive means of converting wood to fermentable sugars because it has been demonstrated under laboratory conditions to achieve up to 95% conversion of cellulose to glucose. The process is also advantageous compared to acid hydrolysis because it proceeds at low temperature (50°C), produces a relatively strong sugar solution (8%) and does not require expensive acid resistant process equipment. A review of recent efforts towards commercializing enzymatic hydrolysis is given by Levelton and Elliott (1983).

The main processing steps in an enzymatic based ethanol plant are:

- feedstock pretreatment to render the cellulose available for hydrolysis;
- enzyme production (cellulase);
- hydrolysis at 50°C and pH 4.8 in batch reactors;

Table 2 Production of Ethanol from Sawmill Residues by Sulphuric Acid Hydrolysis

Nominal Lumber Production (MMfbm/year)	Residue Feedstock Type	Annual Consumption (10^3ODt/year)	Ethanol Produced (ML/year)	Costs[1] Capital (10^6 \$)	Costs[1] O & M (10^6 \$)
50	Chips	36.9	8.7	20.4	1.42
	Sawdust & shavings	24.8	5.9	16.1	1.09
	Chips, sawdust & shavings	62.4	14.7	27.8	1.78
100	Chips	73.9	17.4	30.9	1.92
	Sawdust & shavings	49.7	11.7	24.3	1.62
	Chips, sawdust & shavings	123.5	29.1	42.0	2.89
150	Chips	110.8	26.1	39.5	2.75
	Sawdust & shavings	74.4	17.5	30.9	2.12
	Chips, sawdust & shavings	185.0	43.6	53.8	4.37

[1] 1988 base year

- fermentation of hexose sugars;
- azeotropic distillation;
- yeast and mycelia byproduct dryer.

Mycelia from enzyme production and excess yeast from fermentation are produced as plant by-products and may be sold as a protein source. The cellulase enzyme is produced under aerobic conditions usually using a strain of Trichoderma Reesei in the presence of a carbon source such as lactose and various nutrients.

The analysis of enzymatic hydrolysis based ethanol plant conducted in this study is based on the process and cost details of the steam explosion pretreatment, hydrolysis and enzyme production sections of a plant considered by Arthur D. Little (1985) in their study of a plant for Jefferson County, New York. The balance of the plant was selected and sized using BIOSIM (Edwards and Wasik, 1989). Pretreatment of the feedstock is done using a steam explosion process. The fiberized material is subsequently hydrolyzed at 50°C for 72 hours using cellulose produced in the plant using Trichoderma Reesei.

The yield of ethanol from ethanol plants coupled to three sizes of sawmill are shown in Table 3. The annual production of ethanol for the nine mill/feedstock combinations are less than those for the corrresponding acid hydrolysis based plants because of conservative assumptions on cellulose hydrolysis. The overall ethanol yields for these plants is 200 L/dry tonne.

Estimates of capital and operating costs for the enzymatic hydrolysis based ethanol plants were made assuming separate feedstock storage and preparation would be provided, but the ethanol plant would be located adjacent to the sawmill (Table 3). Capital costs include enzyme production, pretreatment, hydrolysis, hexose fermentation, azeotropic distillation, byproduct protein drying for sale, boiler, water treatment and other offsites. Operating costs include major items such as enzyme production nutrients, maintenance and operating labour as well as lesser costs for electricity, vehicle fuel and fermentation nutrients.

Capital costs range from \$ 4.66 to \$ 2.07 per annual litre as the plant size increases from 5 to 37.2 ML/year. These are close to twice the cost of similarly sized acid hydrolysis based ethanol plants. The much higher capital cost is a result of the cost of the steam explosion and enzyme production sections of the plants.

Operating and maintenance costs vary from a high of \$ 0.35/L for the smallest plant to a low of \$ 0.21/L for the largest plant.

CONCLUSIONS

1. Based on data presently available on the yield of hexose sugars from wood by enzymatic hydrolysis, acid hydrolysis based plants would yield a greater annual production of ethanol. However, enzymatic hydrolysis has the potential to yield a higher cellulose conversion efficiency and ethanol production than presently possible with acid hydrolysis.

2. The capital and operating costs for enzymatic hydrolysis plants are substantially higher than those for acid hydrolysis plants.

Table 3 Production of Ethanol from Sawmill Residues by Enzymatic Hydrolysis

Nominal Lumber Production (MMfbm/year)	Residue Feedstock Type	Annual Consumption (10^3ODt/year)	Ethanol Produced (ML/year)	Costs[1] Capital (10^6 $)	Costs[1] O & M (10^6 $)
50	Chips	36.9	7.4	29.5	2.36
	Sawdust & shavings	24.8	5.0	23.3	1.73
	Chips, sawdust & shavings	62.4	12.5	40.2	3.22
100	Chips	73.9	14.8	44.5	3.60
	Sawdust & shavings	49.7	10.0	35.1	2.80
	Chips, sawdust & shavings	123.5	24.8	60.4	5.57
150	Chips	110.8	22.3	56.7	4.98
	Sawdust & shavings	74.4	15.0	44.6	3.61
	Chips, sawdust & shavings	185.0	37.2	76.9	7.98

[1] 1988 base year

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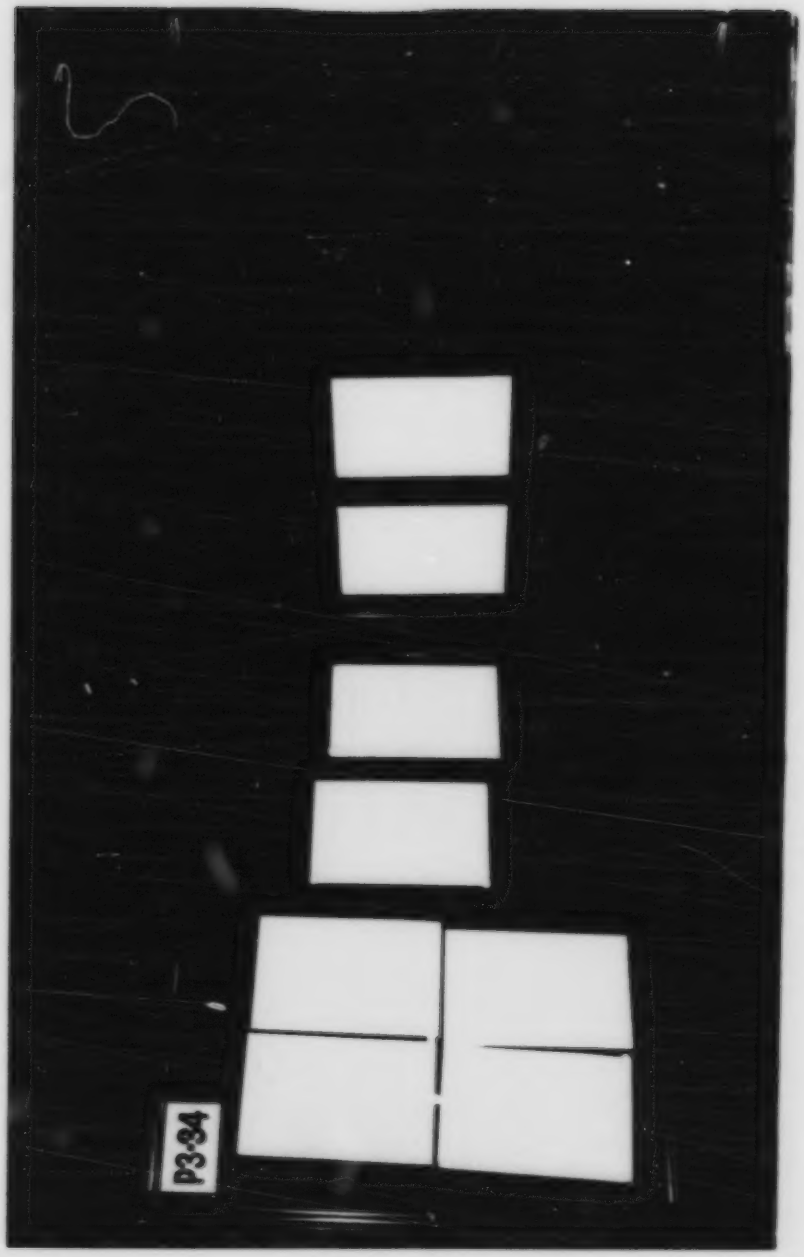
P3-34

EMISSIONS PERFORMANCE OF ETHANOL-CONTAINING TRANSPORTATION FUELS

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Abstract

At the international conference on the changing atmosphere, held in Toronto in 1988, scientists warned of the grave environmental consequences of global warming (greenhouse effect) resulting from increased concentrations of carbon dioxide in the atmosphere. Ethanol derived from biomass is believed to be able to reduce the net atmospheric carbon dioxide contribution by the transportation sector because carbon emitted by combustion processes is recycled between biomass and the atmosphere. Ethanol can be used in its neat form and as a component of blends as an alternative to conventional petroleum-based transportation fuels.

The present paper deals with the environmental implications of exhaust and evaporative emissions resulting from the use of ethanol containing fuels in the transportation sector.

Sommaire

À la conférence internationale sur les changements atmosphériques qui s'est tenue à Toronto en 1988, les scientifiques ont mis le monde en garde contre les graves conséquences environnementales qui résulteraient d'un réchauffement de la planète (effet de serre) en raison de l'augmentation de la concentration de gaz carbonique dans l'atmosphère. On estime que l'utilisation de carburants à base d'éthanol provenant de la biomasse aiderait à réduire la production nette d'oxyde de carbone puisque cela représenterait un recyclage de la biomasse. L'éthanol peut être utilisé seul ou en mélange, en remplacement des carburants conventionnels à base de pétrole.

Le présent document traite des effets sur l'environnement des émissions provenant des gaz d'échappement et des pertes par évaporation résultant de l'utilisation de carburants contenant de l'éthanol dans les moyens de transport.

INTRODUCTION

Concerns about dependence on imported petroleum and increasing atmospheric pollution are motivating many countries to search for alternative fuels. Non-petroleum derived alcohols, especially ethanol and methanol, appear to be promising candidates for use in the transportation sector.

Ethanol, which can be produced by the fermentation of a variety of biomass feedstocks, has been gaining considerable attention. In the United States at the present time approximately 800 million gallons of ethanol, primarily produced from corn, are used each year in a ten percent blend with gasoline (gasohol). Production has been subsidized for a number of years to assist the agricultural sector.

Ethanol mixed in gasoline in concentrations of up to 20 volume percent (vol.%) produces blends which can be used in spark ignition engines without requiring any significant

alterations (1). For higher concentrations of ethanol in gasoline or for neat ethanol a number of changes in the engines are required. Ethanol can also be used as a cosolvent in methanol-gasoline low level blends. The use of ethanol in diesel engines is possible by assisting its ignition behaviour either by adding special chemicals or by using spark or glow plugs.

Proponents have argued that ethanol produced from biomass offers the opportunity to reduce the net atmospheric carbon dioxide (CO_2) contribution by the transportation sector because carbon emitted by the combustion process is recycled between biomass and the atmosphere. The use of ethanol-containing fuel affects the emissions of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx) and particulates depending on engine type and manner of fuel usage. This paper focuses on these environmental implications of ethanol-containing transportation fuels.

GLOBAL WARMING IMPLICATIONS

The problem of increasing atmospheric CO_2 leading to possible future climatic changes has attracted considerable attention in recent years. CO_2 along with other trace gases such as nitrous oxide (N_2O), methane (CH_4), chlorofluoro carbons (CFC's) and tropospheric ozone are transparent to solar short-wave radiation but absorb and emit long-wave thermal radiation. Thus they trap solar heat and cause atmospheric warming. Consequently, these gases are referred to as greenhouse gases.

Transportation fuel is produced from fossil and renewable resources. At the present time combustion of fossil fuels - primarily oil, gas and coal - meets about 80% of the global energy demand.

Coal is the most intensive CO_2 generator followed by oil and gas. Biomass is the least intensive but depends on how the fuel cycle is managed. If feedstock production equals consumption, the carbon is merely being cycled between terrestrial biota and the atmosphere and the use of ethanol produced from biomass minimizes the net CO_2 generation as compared to the use of fossil fuels. However, if forests or other ecosystems are cleared or harvested more rapidly than they can be regrown, the standing biomass is, in effect, being 'mined' and CO_2 emissions from combustion increase the carbon content of the atmosphere (2).

Marland and Turhollow (3) estimated CO_2 emissions during the entire cycle of ethanol production from biomass (corn) based on the energy consumption in agriculture for growing corn as well as during the corn to ethanol conversion process. The CO_2 emissions during ethanol production from biomass can vary a great deal depending upon the type of biomass used, geographic variability, agricultural practices, and changes in processes and process efficiencies. Using data from various sources Marland and Turhollow arrived at the average value of 1.7343 kg of CO_2 for the entire process of biomass production to ethanol conversion per kg of ethanol produced.

CO_2 generation during production and combustion of ethanol and gasoline are:

Ethanol

Lower heating value
= 11500 BTU/lb. (4)
= $11500 \times 1.055 \times 10^3 \times 2.2046 \times 10^{-6}$
= 26.75 megajoule/kg

CO_2 emissions during production
= $1.7343/(26.75 \times 10^{-3})$ = 64.84 kg/gigajoule (gj)

Marland and Turhollow allocated 51.1% of the total energy input to ethanol and the remainder to by-products.

CO_2 emissions ascribable to production
= 64.84×0.511 = 33.13 kg/gj

CO_2 emissions during combustion
= $(88/46) \times 1/(26.75 \times 10^{-3})$
= 71.52 kg/gj

Therefore total CO_2 emissions during production and combustion
= 104.65 kg/gj

Gasoline

Lower heating value
= 18500 BTU/lb. (4)
= $18500 \times 1.055 \times 10^3 \times 2.2046 \times 10^{-6}$
= 43.03 megajoule/kg

The numbers in parenthesis designate references given at the end of this paper.

Gasoline contains about 85% carbon by weight.

CO_2 emissions during combustion
$= 0.85 \times (44/12) \times 1/(43.03 \times 10^{-3})$
$= 72.43$ kg/gj

Assuming energy consumed in petroleum production and refining to be 12% of the energy content of the final product (3,5) CO_2 emissions during production
$= 72.43 \times 0.12$
$= 8.69$ kg/gj

Therefore total CO_2 emissions during production and combustion = 81.12 kg/gj

The above calculations show that CO_2 emissions during combustion are less for ethanol than for gasoline but 29% higher for production and combustion combined. However, the carbon cycle for the combustion of biomass ethanol is a closed cycle. Hence it may be assumed that CO_2 emisions resulting from ethanol combustion are balanced by CO_2 capture through photosynthesis by the next biomass crop. Based on the assumption of a closed carbon cycle the use of biomass ethanol will reduce the CO_2 emissions by about 59% as compared to gasoline on same energy content basis. Extending the calculations to ethanol blends it can be shown that gasohol offers about 4% reduction in CO_2 emissions as compared to gasoline.

In the above discussion it has been assumed that ethanol and gasoline have equal combustion efficiencies when used in automobile engines. Proponents of ethanol claim that ethanol provides higher efficiency than gasoline. If this is correct, then CO_2 emissions from ethanol would be less than those indicated by energy content calculations.

OTHER ENVIRONMENTAL IMPLICATIONS

In North America the use of ethanol as a transportation fuel is limited to low level blends (up to 10 vol.% ethanol in gasoline). When ethanol is added to gasoline it modifies the fuel properties and affects the nature and quantities of exhaust and evaporative emissions from vehicles. From the environmental perspective the following changes are of particular interest:

(a) Ethanol contains about 35 wt.% oxygen. The presence of oxygen in fuel generally results in the reduction of CO emissions (6). Depending on the fuel metering system and control technology used on the vehicle ethanol blends may offer CO reductions of up to 25% or 30%.

(b) Ethanol has a blending octane value of about 110 as compared to 92 for unleaded premium gasoline. Thus blending ethanol in gasoline enhances its octane value. As an octane enhancer ethanol can partially replace aromatics in gasoline which result in emissions of benzene, a known carcinogen.

(c) Ethanol forms azeotropes with a number of hydrocarbons present in gasoline. This phenomenon results in a non-ideal increase in the Reid vapor pressure (Rvp) for the blend. Typically for a 10% ethanol blend the Rvp increase is about 7 kilopascals. The Rvp of ethanol-gasoline blends can be matched with that of base gasoline by removing butane or other volatile components from the blend's gasoline part. However, at the present time the Rvp of gasohol in the U.S. is not matched with gasoline Rvp. Higher Rvp of ethanol-gasoline blends (which are not matched for volatility) results in higher evaporative and exhaust emissions of hydrocarbons as compared to base gasoline (7).

(d) Aldehyde emissions from ethanol-gasoline blends are generally higher than those from gasoline. However, three-way catalytic converters which are now used on all new vehicles are very efficient in reducing aldehyde emissions. Hence aldehyde emissions from new vehicles are expected to be substantially lower even when operating on blends as compared to older vehicles operating on gasoline.

(e) The HC emissions from ethanol-gasoline blends differ significantly in composition and reactivity when compared to gasoline HC emissions. Those from blends consist largely of non-oxygenated HC compounds, alcohols and aldehydes. Alcohols have much lower reactivities than gasoline HC's, whereas aldehydes are highly reactive. Hence the overall ozone forming potential of ethanol-gasoline blends is considered to be about the same as of gasoline (8).

(f) NOx emissions from ethanol-gasoline blends are comparable to those from gasoline.

Bailey and Meagher (8) classified and compared the emissions data for ethanol-gasoline blends from a number of sources by emissions control system category namely, no catalyst, oxidation catalyst, and three-way catalyst with closed loop (TWC-CL). For the sake of ready reference the exhaust and evaporative emissions data have been reproduced from their publication in Tables 1 and 2 respectively.

A limited number of exhaust emission tests on two vehicles using blends of 5 and 15 vol.% ethanol in gasoline were conducted at the Vehicle Emissions Testing Laboratory (VETL) of Environment Canada. All tests were performed in accordance with the U.S. Federal Test Procedure. The measurements of exhaust emissions included regulated emissions of CO, HC and NOx as well as unregulated emissions of alcohol and aldehydes. The alcohol was sampled and analyzed using the water-impinger/GC technique while aldehydes were measured using the DNPH cartridge/HPLC technique. The results are shown in Table 3. The results of aldehyde speciation on exhaust emissions samples are given in Table 4.

The VETL test results show similar trends for changes in emissions from vehicles operating on ethanol blends compared with gasoline as was observed by Bailey and Meagher (8). Aldehyde speciation results of exhaust emissions samples from non-catalyst vehicle identified at least seven compounds for all the fuels tested, whereas exhaust samples from the TWC-CL equipped vehicle showed only three compounds, namely formaldehyde, acetaldehyde and acetone. The results confirm that the use of TWC-CL significantly reduces the quantity and complexity of aldehyde emissions.

CONCLUSIONS

1. Based on the assumption of a closed biomass/atmosphere carbon cycle ethanol derived from biomass may reduce CO_2 emissions by roughly 60% as compared to gasoline on an equal energy basis. For gasohol (10 vol.% ethanol) this reduction is about 4%.

2. Gasohol reduces CO emissions and increases aldehyde emissions. However, the latter can be significantly reduced with the use of three-way catalytic converters.

3. The overall ozone and acid rain forming potential of gasohol is about the same as of gasoline.

ACKNOWLEDGEMENT

The authors are grateful to F.C. Hendren and P. Howes for conducting the vehicle emissions tests at the VETL referred to in this paper.

DISCLAIMER

Although this paper has been supported by Environment Canada it has not been vetted for policy implications and therefore does not necessarily reflect the views of the Department; an official endorsement should not be inferred.

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TABLE 1 - Exhaust Emissions (8)

Emission classification	Catalyst type*	Average emissions concentration: Gasoline	Average emissions concentration: Ethanol blend	Percent change in emissions for blends
CO	None	13.45 g/km	9.88 g/km	-26.5
	Oxid	4.72	3.12	-33.9
	TWC-CL	2.78	2.17	-21.9
NO_2	None	2.33 g/km	2.19 g/km	- 6.0
	Oxid	0.88	0.93	5.7
	TWC-CL	0.34	0.39	15.0
HC	None	1.92 g/km	1.86 g/km	- 3.1
	Oxid	0.39	0.32	-18.0
	TWC-CL	0.19	0.20	5.3
Ethanol	None	8.92 mg/km	143.5 mg/km	1510.0
	Oxid	0.64	5.77	800.0
	TWC-CL	1.37	3.25	137.0
Aldehydes	None	75.9 mg/km	117.0 mg/km	54.2
	Oxid	7.0	9.5	36.0
	TWC-CL	3.8	6.0	58.0

*Oxid = oxidation catalyst; TWC-CL = three way catalyst, closed loop.

TABLE 2 - Evaporative Emissions (8)

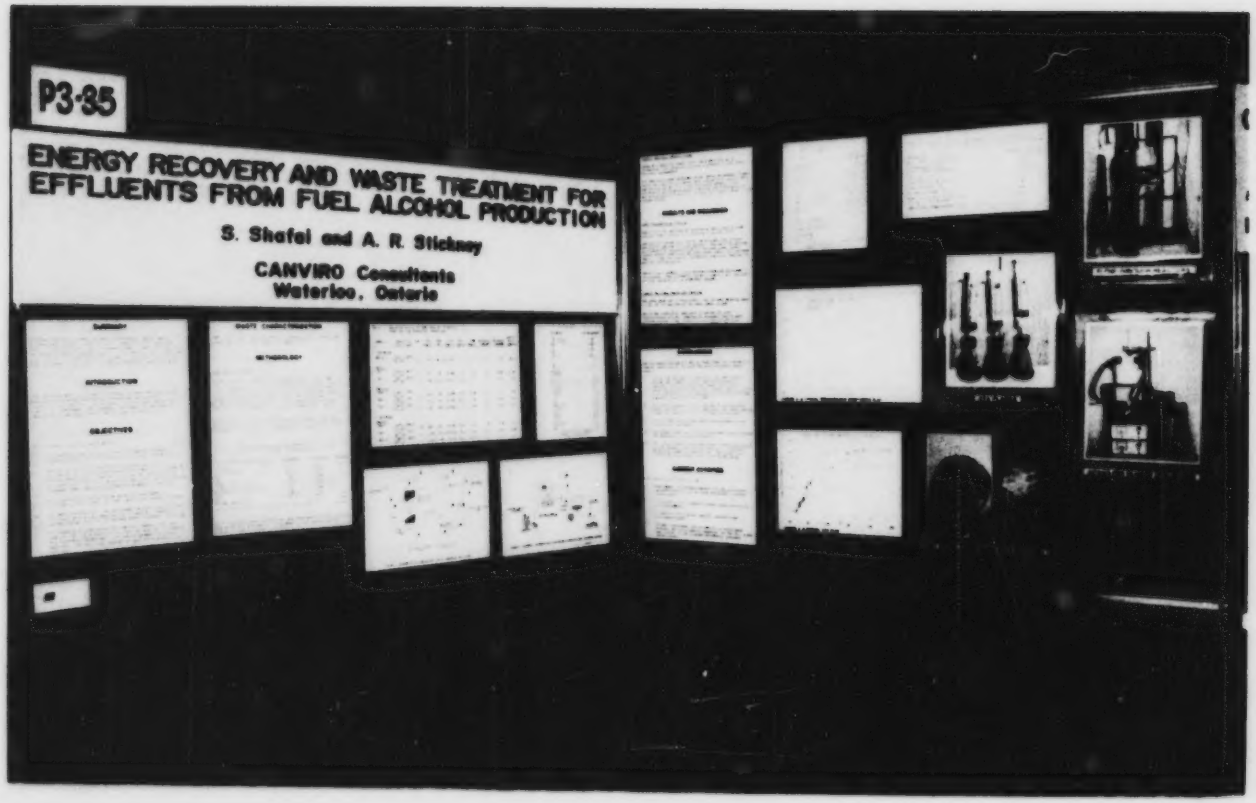
Chemical component	Portion of evaporative emissions test	Average emissions per test: Gasoline (g)	Average emissions per test: Ethanol blends (g)	Percent change in emissions
HC	Diurnal	2.22	2.99	34.3
HC	Hot Soak	2.37	5.05	113.0
Ethanol	Total	0.076	1.36	1700.0

TABLE 3 - Exhaust Emissions Results from VETL

Emission classification	Catalyst Type	Average Composite Emissions from: Gasoline	5% Ethanol Blend	15% Ethanol Blend	Percent Change in Emissions for: 5% Ethanol Blend	15% Ethanol Blend
CO (g/km)	None	8.5	7.2	5.4	-15.3	-36.5
	TWC-CL	3.3	2.1	1.8	-36.4	-45.5
NOx (g/km)	None	0.89	0.91	0.72	+ 2.3	-19.1
	TWC-CL	0.22	0.24	0.37	+ 9.1	+68.2
HC (g/km)	None	1.20	1.16	1.17	- 3.3	- 2.5
	TWC-CL	0.16	0.17	0.11	+ 6.3	+31.3
Ethanol (mg/km)	None	-	30.5	135.4		
	TWC-CL	-	1.3	2.9		
Total Aldehydes (mg/km)	None	43.1	74.4	123.1	+72.6	+186.1
	TWC-CL	13.9	14.0	22.4	+ 0.7	+61.2

TABLE 4 - Aldehyde Speciation Results from VETL

Emission Classification	Catalyst Type	Average Composite Emissions (mg/km) from: Gasoline	5% Ethanol Blend	15% Ethanol Blend
Formaldehyde	None	18.3	28.2	40.5
	TWC-CL	9.5	10.3	18.7
Acetaldehyde	None	10.3	22.2	55.1
	TWC-CL	2.9	2.5	3.1
Acrolein	None	1.8	6.1	8.6
	TWC-CL	-	-	-
Acetone	None	3.2	4.4	4.5
	TWC-CL	1.3	-	0.6
Propionaldehyde	None	4.3	4.7	5.8
	TWC-CL	-	-	-
Crotonaldehyde	None	0.9	2.2	2.2
	TWC-CL	-	-	-
Benzaldehyde	None	4.3	6.6	6.4
	TWC-CL	-	-	-
Total Aldehydes	None	43.1	74.4	123.1
	TWC-CL	13.7	14.0	22.4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ENERGY RECOVERY AND WASTE TREATMENT FOR EFFLUENTS FROM FUEL ALCOHOL PRODUCTION
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DEVELOPMENT AND APPLICATION OF ENERGY RECOVERY AND WASTEWATER TREATMENT SYSTEMS FOR WASTE STREAMS GENERATED DURING THE PRODUCTION OF FUEL ALCOHOL

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The overall objectives of the project were to characterize and assess the waste streams generated during the processing of sugars, starch-derived sugars and sugars derived from cellulosic feedstocks to produce fuel grade alcohol and to conduct a comprehensive treatability program to develop process standards for waste treatment, with emphasis on energy recovery and utilization.
Based on the findings of an extensive literature review and identification and characterization of waste streams generated during the production of fuel alcohol, two waste streams were selected for treatability or toxicity analysis. In selecting appropriate treatment technologies, an emphasis was placed on the potential for energy recovery and utilization.
A steam explosion pretreatment condensate (SEPC) waste stream was treated anaerobically. Bench-scale UASB and fixed film anaerobic reactors were used. SEPC was found to be anaerobically biodegradable. COD removals of 80-95% were achieved at 8-10 kg COD/m^3.d organic loadings. Batch ATA analysis was performed on a lignin recovery waste stream.
Based on the results of the treatability testing, process standards and design criteria were developed for the full-scale implementation of waste treatment technologies. The final report includes process designs, energy balances, and economic assessments including the estimation of the anticipated capital, operation and maintenance costs.

Le projet avait comme objectifs globaux de caracteriser et d'évaluer les rejets produits au cours du traitement de sucres, de sucres tirés de l'amidon et de sucres tirés de matières cellulosiques en vue de fabriquer de l'alcool de qualité combustible, et de réaliser une étude exhaustive sur la traitabilité afin d'élaborer des normes régissant les procédés de traitement des déchets, en tenant compte de façon particulière de la récupération d'énergie et de l'utilisation de l'énergie récupérée.
En se basant sur les résultats d'une étude approfondie de la littérature et sur l'identification et la caractérisation des rejets produits au cours de la fabrication d'alcool distiné à être utilisé comme combustible, on a choisi deux types de rejets en vue d'en déterminer la traitabilité ou la toxicité. On a surtout tenu compte, lors de la sélection des techniques de traitement appro-priées, de la mesure dans laquelle il serait possible de récupérer de l'énergie et d'utiliser l'énergie récupérée.
On a soumis à un traitement anaérobie un rejet constitué d'un condensat de prétraitement par explosion à la vapeur (SEPC). On a utilisé des réacteurs de laboratoire UASB et des réacteurs anaérobies à film fixe. On a constaté que le SEPC était biodégradable. On a obtenu des diminutions de 80-95% de la DCO à un apport en matières organiques de 8-10 kg DCO/m^3/jour. On a effectué par lot des analyses ATA sur les rejets provenant de la récupération de la lignine.
En se basant sur les résultats des essais de traitabilité, on a élaboré des normes pour les procédés et des critères de conception pour l'application à l'échelle industrielle des techniques de traitement des déchets. Le rapport final renferme des données sur la conception des procédés et sur les bilans énergétiques, ainsi que des évaluations économiques dont l'estimation des coûts en capital, des coûts d'exploitation et des frais d'entretien.

INTRODUCTION

The project was initiated by Energy, Mines and Resources Canada to provide wastewater characterization and treatability data and to estimate capital and operating costs for treatment and disposal systems for wastewater resulting from the production of fuel alcohol.

The overall objectives of the project were to characterize and assess the waste streams generated during the processing of sugars, starch-derived sugars and sugars derived from cellulosic feedstocks to produce fuel grade alcohol, and to conduct a comprehensive treatability program to develop process standards for waste treatment, with emphasis on energy recovery and utilization.

The specific objectives were as follows:

1. To identify and characterize the waste streams generated during the production of fuel grade alcohol.

2. Based on the waste stream characterizations, to evaluate and select appropriate wastewater treatment technologies (with emphasis on energy recovery and utilization) for each waste stream, and identify waste streams that require further treatability analysis.

3. To prioritize and perform selected wastewater treatability studies on the identified waste streams.

4. To develop process standards and design criteria for the full-scale implementation of waste treatment technologies for the selected waste streams including process designs, energy balances and economic assessments.

5. To prepare a comprehensive report summarizing the results of the treatability studies and of the energy and economic assessment including example process designs, capital, and operation and maintenance costing.

Waste Streams Selection

From discussions with organizations involved with the production of fuel grade alcohol, waste streams generated during the various processes were identified and evaluated as to their suitability for anaerobic technology for energy recovery and waste treatment. The waste streams identified were evaluated on the basis of the following considerations:

- Physical and chemical characteristics
- Potential quantities of waste produced (short- and long-term)
- Energy recovery and utilization potential
- Current waste treatment, disposal and/or utilization practices for similar waste streams

A steam explosion pretreatment condensate (SEPC) was selected for initial pilot testing for the following reasons:

- Common waste stream to most Canadian wood-to-ethanol processes
- Large volume generated in the process
- Waste stream was currently available in sufficient quantities to run pilot studies
- Lack of treatability data on this waste stream

A second waste stream from the lignin recovery operation was evaluated for possible anaerobic toxicity effects by using a standard anaerobic toxicity assay (ATA) testing procedure.

Waste Streams Characterization

A complete waste stream characterization was conducted at the outset of the treatability studies to determine the physical and chemical characteristics of the SEPC waste and the lignin recovery waste. The results are presented in Tables 1 and 2, respectively.

Table 1. Characteristics of SEPC Samples Produced Under Varying Operating Conditions

Sample	Operating Conditions	pH	TS (mg/L)	TVS (%)	COD (mg/L)	TP (mg/L)	TKN (mg/L)	Methanol (mg/mL)	Furfural (mg/mL)	Acetic Acid (mg/mL)
1) Hardwood										
Batch 1	2 min, 320°C, 325 psi	3	575	96	21,300	<1	0.9	2.3	4.8	8.5
Batch 2										
Run 1	2 min, 190°C, 167 psi		25	100	3,090	0.07	1.33	1.4	0.06	0.08
Run 2	2 min, 230°C, 391 psi		720	97.3	20,360	0.12	1.27	1.9	5.1	7.0
Batch 3										
Run 1	2 min, 190°C, 167 psi	2.5	135	100	4,500	0.14	0.58	1.0	0.6	1.4
Run 2	2 min, 219°C, 322 psi	2.5	550	100	19,400	<0.07	1.15	2.1	4.9	6.6
Run 3	2 min, 229°C, 391 psi	2.5	500	100	15,860	0.17	1.10	1.0	2.9	5.1
2) Softwood										
Batch 1										
Run 1	2 min, 200°C, 212 psi	2.8	360	250	8,990	<0.2	<1.0	1.9	2.4	1.9
Run 2	2 min, 210°C, 262 psi	2.3	1,985	1,335	10,700	<0.2	<1.0	1.7	1.4	1.4
Run 3	2 min, 224°C, 330 psi	2.2	2,125	1,535	9,310	<0.2	<1.0	2.2	1.2	1.6

Table 2. Lignin Recovery Waste Characterization Data

Parameter	Concentration*
pH	1.8
COD (total)	4,490
COD (soluble)	4,200
BOD	1,480
TS	16,360
TVS	7,080
TDS	13,660
VDS	5,465
TP	4.64
NH_3-N	5.6
TKN	4.8**
Phenol	77.2
Metals	
Aluminum	4.57
Barium	0.21
Beryllium	<0.005
Boron	<0.01
Cadmium	<0.012
Calcium	29.2
Chromium	0.18
Cobalt	<0.03
Copper	0.25
Iron	24.8
Lead	0.34
Magnesium	2.29
Manganese	0.14
Nickel	<0.02
Phosphorus	0.14
Silver	<0.02
Sodium	3,130
Strontium	<0.04
Vanadium	<0.01
Zinc	0.30

*All concentrations in mg/L except for phenol (in µg/L) and pH.
**Interferences detected.

As shown in Table 1, the SEPC wastewater characteristics varied considerably. Waste characteristics were dependent on the production process operating conditions (time, pressure, and temperature). The chemical oxygen demand (COD) of the condensate ranged from 3,000 to approximately 20,000 mg/L. Furfural concentrations ranged from 60 to 5,100 mg/L. The strongest waste was generated at 391 psi pressure, 230°C temperature, and at 2 minutes operating time.

The lignin recovery waste (Table 2) was relatively weak in comparison (4,500 mg COD/L), but was thought to be potentially inhibitory to methanogenic bacteria.

EQUIPMENT AND METHODS

SEPC Waste Stream Continuous Flow Testing

Three anaerobic flow-through reactors were used. Two reactors (R_1, R_2: 16.9 L each) were upflow sludge blanket (UASB) type, and one (R_3: 13.7 L) was a downflow fixed film (FF) reactor. Figure 1 is a schematic of the two reactor types. The pre-acidification tank (PAT) upstream of R_1 and R_2 was not used for reactor 3. Except for the PAT unit and the reactor type, the set up for R_3 was identical to R_1 and R_2. The three reactors were seeded with anaerobic sludge from a municipal digester. They were operated at 35°C (mesophilic growth temperature range).

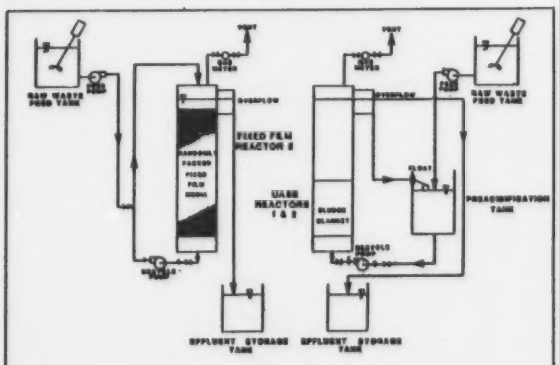


FIGURE 1: SCHEMATIC OF LABORATORY SCALE ANAEROBIC REACTORS

After starting the reactors on municipal digester sludge and cheese whey, the three reactors were fed a 1:10 dilution of steam explosion pretreatment condensate (SEPC). SEPC was diluted because the characterization data had shown that the level of furfural contained in the condensate is approximately ten times higher than toxic levels reported in the literature for unacclimated anaerobic microorganisms. The rate of dilution was, however, decreased as the anaerobic microorganisms became acclimated to the presumably toxic compounds contained in the condensate.

Performance of the anaerobic reactors was monitored for approximately 6 months. The performance monitoring schedule followed in this study is summarized in Table 3. Whenever steady operating conditions for one of the three reactors was achieved (as signalled by consistently low effluent COD concentrations and reactor VA/BA ratios, steady biogas production, and optimum effluent pH values), the organic loading rate for that reactor was increased. In most cases, performance of the anaerobic reactors improved with time after every increase in loading.

Table 3. Performance Monitoring Schedule for the SEPC Treatability Studies (flow-through reactors)

Parameter/Analysis	Influent	Effluent	Biogas
Volume	daily	daily	daily
Temperature	daily	daily	-
pH	daily	daily	-
TS	2/wk	2/wk	-
TVS	3/wk	2/wk	-
Total volatile acids	3/wk	2/wk	-
Bicarbonate alkalinity	3/wk	2/wk	-
COD	/wk	2/wk	-
BOD_5	1/month	1/month	-
Biogas analysis	-	-	1/wk

Reactors 1 (on day 86) and 2 (on day 85) were modified to include a pre-acidification stage. This was done to evaluate the effect of separating the hydrolysis/acidification stages from the methanogenic stage. The pre-acidification tanks (PATs) also acted as equalization tanks prior to anaerobic reactor.

In order to investigate the effect of higher furfural concentrations on the performance of the anaerobic units, the SEPC feed for reactors 2 (on day 164) and 3 (on day 171) was spiked with higher levels of furfural.

Despite significant organic reductions, effluents from the anaerobic reactors were still relatively high in BOD. A pilot-scale activated sludge system (10 litres volume) was constructed and went into operation on day 118. A schematic of the activated sludge system is shown in Figure 2. The activated sludge system was used for aerobic polishing of the anaerobic effluents. The system was operated in high-rate mode.

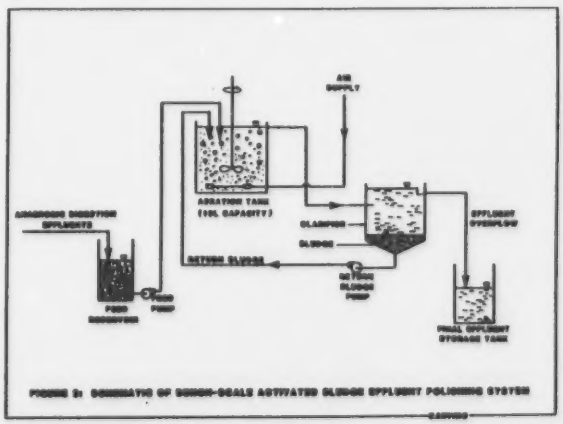


FIGURE 2: SCHEMATIC OF BENCH-SCALE ACTIVATED SLUDGE EFFLUENT POLISHING SYSTEM

Lignin Recovery Waste Stream ATA Testing

Anaerobic toxicity assay (ATA) tests were set up to investigate the possible inhibitory effects of the lignin recovery wastewaters.

The ATA tests were performed using 125 mL Erlenmeyer flasks which were placed in a water bath inside an incubator that was maintained at 35°C. Varying concentrations of the wastewater, a nutrient supplement, and sludge obtained from a municipal digester were transferred into the ATA units that were kept oxygen-free during dispensing by continuous gassing with a 30% CO_2/70% N_2 mixture. All flasks were spiked with an aliquot of volatile organic acids.

In conjunction with the ATAs, a set of spiked controls were run. The inhibitory effect of the wastewater was determined by comparing the differences in methane production rates in the test units with those in the spiked blanks.

RESULTS AND DISCUSSION

SEPC Treatability Testing

Results of the performance monitoring tests were plotted against time. Figure 3 illustrates a typical plot. In addition to influent and effluent COD, other parameters such as gas production, influent and effluent pH, reactor total alkalinity, bicarbonate alkalinity, and volatile acids/bicarbonate alkalinity (VA/BA) ratios were also analyzed.

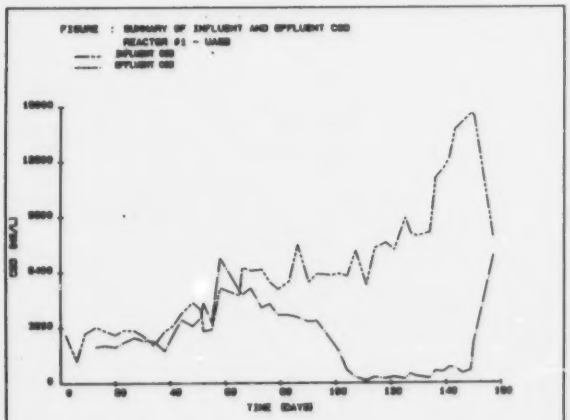


Figure 3: A Typical Performance Monitoring Plot

It was noted that biogas production rates decreased and reactor performance deteriorated initially after every large increase in organic loading. In most cases, however, performance of the anaerobic reactors improved with time indicating a more stabilized operation at progressively higher loading rates.

In the later stages of the treatability testing, organic loading to the anaerobic reactors was increased at considerably faster rates, without a significant drop in performance. This is an indication of a progressive acclimation of the anaerobic microorganisms to SEPC.

In an attempt to quantify the reactors' performance trends and using the performance plots such as one shown in Figure 3, the entire treatability period was divided into 6 shorter monitoring periods for each reactor. The selected periods were generally representative of the stabilized (quasi-steady-state) conditions achieved after every load increase. Table 4 lists the typical information that was compiled for each monitoring period.

Table 4. Typical Information Compiled for Each Performance Monitoring Period (Reactor 1, UASB)

Parameter	Period 5 (day 136-199)
Temperature (°C)	34
HRT (days)	1.6
Dilution factor (%)	78
$COD_{(infl)}$ (g/L)	13.8 (1.4) n=6
COD loading rate (g COD/L/d)	8.6 (0.88) n=6
$pH_{(effl)}$	7.5 (0.15) n=14
COD reduction (%)	95 (1.05) n=6
Total volatile acids (mg/L)	183 (130) n=5
Total alkalinity (mg/L)	2567 (229) n=5
VA/BA ratio	0.08 (0.07) n=5
Specific biogas production (LCH_4/g COD added)	0.30
Specific biogas production (LCH_4/g COD removed)	0.32
Methane content (% of volume)	69.2
Biogas production (L/d)	63.7 (68.3) n=14

( ) = standard deviation
n = number of samples

Using the performance plots (Figure 3) and performance data such as those summarized in Table 4, and based on the trends observed for the anaerobic reactors, design criteria were developed for the large-scale implementation of the anaerobic treatment systems. Table 5 is a summary of the process standards developed in this study. The information given in Table 5 will be used for the scale-up of the anaerobic systems.

Table 5. Design Criteria Developed from the Treatability Study, Waste Characterization and Literature Review

Parameter	Design Criteria
Mill size (tons wood/day)	1,000
Condensate volume (L/ton wood processed)	450
$COD_{(infl)}$ (mg/L)	20,000
Loading (kg COD/m³.d)	7
COD reduction (%)	95
Biogas methane content	60%
Specific biogas production (LCH_4/g COD removed)	0.30
Operating temperature (°C)	35

Addition of the pre-acidification stage to the two UASB reactors was found to be unnecessary. This finding was based on the comparison of R_1 and R_2 performances after day 126 when the reactor 2 (PAT) was removed. The R_2 performance did not deteriorate after the PAT removal and was comparable to R_1 (which was still equipped with PAT) performance. The observed improvement in performance at the initial stages of PAT installation was, therefore, attributed to the continued acclimation of the anaerobic bacteria to the SEPC feed. Equalization of the SEPC waste stream may, however, be required in the full-scale operation as the condensate temperature will be well above the optimum (35°C) for mesophilic methanogenesis.

UASB reactors R_2 (on day 164) and R_3 (on day 171) were spiked with higher levels of furfural. Organic loadings were also increased concurrently. The high initial organic loading - furfural concentration combination proved to be detrimental to the digesters' performance. In an attempt to correct the problem, the organic loadings were subsequently lowered. As the reactors' performance bounced back with lowered loadings, furfural concentrations were systematically increased. An incremental increase in furfural concentration resulted in little or no drop in performance. It was concluded that at lower organic loadings, higher concentrations of furfural (up to 8 g/L) would be tolerated by acclimatized microbial population.

Performance of the activated sludge system, started on day 118, improved considerably with time. Start-up problems, such as the poor sludge settling characteristics and the impaired microbial activity characteristic of most activated sludge systems, gradually improved as the bacterial population responsible for waste stabilization acclimatized to the new substrate. The activated sludge system's performance continued to improve and approached steady-state conditions with the continued operation of the system at the desired operating conditions.

Satisfactory performance of this aerobic waste stabilization system is indicative of the effectiveness and suitability of the activated sludge process for the treatment of the anaerobic digestion effluents.

Lignin Recovery Waste ATA Testing

To investigate the possible inhibitory effects of the lignin recovery wastewaters, anaerobic toxicity assay (ATA) tests were set up. Based on the data obtained from the waste characterization, varying concentrations of the wastewater were used. The ATAs were run in triplicate. The volumes selected were 5, 10, 20, 40 and 60% of the total assay volume.

Daily gas production data were collected for each concentration series. Cumulative averaged results were plotted against time. Figure 4 is a typical ATA plot. The inhibitory effect of the wastewater was determined by comparing differences in methane production rates in the test units with those in the spiked blanks.

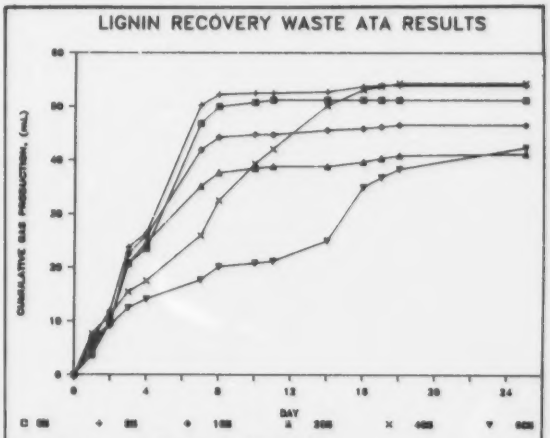


Figure 4: A Typical ATA Plot

It was concluded that the lignin recovery wastewater stimulates growth slightly at low concentrations but is inhibitory at higher concentrations. It was further concluded that given sufficient time, higher rates of methane production could be achieved at even higher concentrations. This is attributed to the acclimation of the anaerobic microorganisms to the new substrate.

Using the gas production data for the first 14 days of ATA testing, the coefficient of inhibition for this waste was estimated to be in the 30-40% range.

CONCLUSIONS

The following conclusions may be drawn from the treatability testing conducted on the selected wood-to-ethanol wastewaters:

1) Characteristics of the steam explosion pretreatment condensate (SEPC) waste stream varied with the production process operating conditions. COD of the condensate ranged from 3,000 to 20,000 mg/L.

2) COD of the lignin recovery waste stream was lower in comparison. COD of this wastewater measured 4,500 mg/L.

3) Performance of the flow-through reactors improved with time indicating a more stabilized operation at progressively high organic loadings. This is an indication of the progressive acclimation of the anaerobic microorganisms to SEPC.

4) Full-scale treatment facilities may be designed for above 7 kg COD/m³.d organic loadings. At these loading rates, COD removals of up to 95% may be achieved.

5) A pre-acidification stage before methanogenesis was found to be unnecessary.

6) At lower organic loadings, high concentrations of furfural (up to 8 g/L) would be tolerated by acclimated microbial population.

7) Aerobic polishing of the anaerobic digestion effluents for further BOD reduction may be required where effluents are disposed of in surface waters.

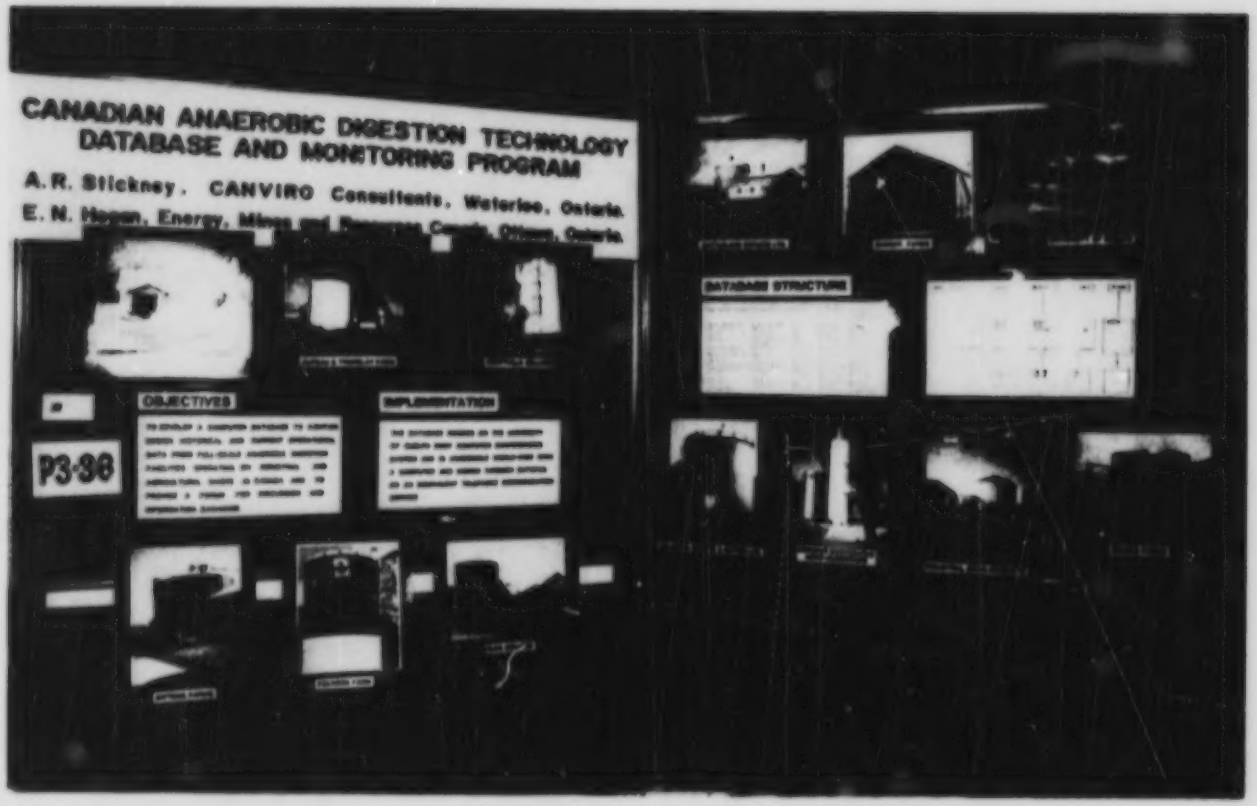
8) Activated sludge was found to be suitable for polishing the anaerobic digestion effluents.

9) The lignin recovery waste was found to stimulate growth at low concentrations but is inhibitory to methanogenesis at higher concentrations. The inhibition coefficient was found to be in the 30-40% range.

Current Activities

The present activities include:

- Development of process designs for the large-scale implementation of the selected wastewater treatment technologies.
- Evaluation of the treatment system energy production and requirements.
- Estimation of projected capital, operation and maintenance costs.
- Economic assessment and estimation of anticipated monetary and environmental paybacks for the full-scale application of the proposed wastewater treatment technologies.


CANADIAN ANAEROBIC DIGESTION TECHNOLOGY
DATABASE AND MONITORING PROGRAM
A.R. Stickney, CANVIRO Consultants, Waterloo, Ontario.
E.N. Hogan, Energy, Mines and
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OBJECTIVES
IMPLEMENTATION
DATABASE STRUCTURE

CANADIAN ANAEROBIC DIGESTION TECHNOLOGY DATA BASE AND MONITORING PROGRAM

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A computer database was developed to monitor full-scale anaerobic digestion facilities operating on industrial and agricultural wastes in Canada. The database contains historical design and current operational data. The database resides at the University of Guelph on the CoSy Computer Conferencing System and is accessible world-wide. Users of the system can contact a wide variety of Canadian and International experts on Anaerobic Technology and exchange design and operational information. The conferencing system is easy to use and can be accessed through DATA PAC by a wide variety of personal computers. During 1989 the database is being expanded to include typical applications of Anaerobic Technology on a wide variety of wastewaters in Canada and a number of other countries.

On a élaboré une base de données informatisée afin de contrôler les installations de digestion anaérobie traitant des déchets industriels et agricoles au Canada. Cette base de données renferme des données historiques sur la conception et sur les paramètres opérationnels actuels. Elle se trouve dans le système de téléconférence par ordinateur CoSy de l'Université de Guelph, et on peut y avoir accès à partir de n'importe où au monde. Les utilisateurs du système peuvent entrer en communication avec une grande variété de spécialistes dans le domaine des techniques anaérobies au Canada et à l'étranger et ainsi échanger des renseignements sur la conception des installations et sur les paramètres opérationnels. Le système de téléconférence est facile à utiliser et on peut y avoir accès par l'entremise de DATA PAC à partir de plusieurs types d'ordinateurs personnels. Au cours de 1989, on améliorera la base de données qui alors comprendra, entre autres, des données sur des applications typiques de techniques anaérobies à une grande variété d'eaux usées au Canada et dans un certain nombre d'autres pays.

A computer database was developed to monitor full-scale anaerobic digestion facilities operating on industrial and agricultural wastes in Canada and to provide a forum for information exchange. The database contains historical design data and current operational data from 18 full-scale anaerobic digestion facilities. The database resides at the University of Guelph on the CoSy Computer Conferencing System and is accessible worldwide.

INTRODUCTION

The application of anaerobic digestion technology to industrial and agricultural wastes is in its infancy in Canada and the availability of adequate engineering design information is extremely limited. In Canada, there are 18 full-scale and large pilot-scale anaerobic digestion systems treating a variety of industrial and agricultural wastes. The engineering design sizing and the actual operational conditions are either not readily available or are published in a number of different formats making comparisons between facilities difficult. The project was designed to bring this information together into one database and to provide a forum for discussion about anaerobic technology.

MATERIALS AND METHODS

Database Development

An inventory of anaerobic digestion systems in Canada was established by contacting federal and provincial government officials, universi-

ties, engineering firms and individuals involved with anaerobic digestion technology. An extensive literature review of project reports, presentations, journals and other publications was conducted.

The data collected was compiled into a standard format and entered into computer data files.

CoSy Computer Conferencing System

The CoSy Computer Conferencing System, developed and operated by the University of Guelph, was selected for the storage of the database. The CoSy system was selected because it is currently being used for a wide variety of similar conferences, is relatively user friendly, and is accessible worldwide, with a computer and modem, through DATAPAC and other similar telephone communication services.

Long-Term Monitoring Program

A long-term monitoring program was established to obtain current operational data and operator comments, questions and suggestions on anaerobic digestion technology. The program involves obtaining copies of operational monitoring sheets and records from sites where this information is collected and recorded, and through monthly sampling where no operational records are currently being kept.

RESULTS AND CONCLUSIONS

Full-Scale Anaerobic Digestion System Inventory

A list of the full-scale Canadian anaerobic digestion facilities contained in the database is presented in Table 1.

Organization of CoSy Database

The CoSy Computer Conferencing System is organized into conferences/topics/messages. The organizational structure of the database is presented in Figure 1. The database contains six conferences and each conference (except INTRO and DISCUSS) contains 18 topics, one for each anaerobic digestion facility. New information is added to a topic in the form of a new message. The six database conferences are as follows:

1. Introduction (INTRO)
   This conference is an introduction to the database. It contains a list of the conferences and a brief description of each one.

2. Digester Design Information (DIGESTERDESIGN)
   This conference contains technical design information.

3. Current Operating Conditions (OPCONDITIONS)
   This conference contains information about the current operating conditions at each site as well as operator notes and observations.

4. Monthly Data Report (MONTHREPORT)
   Information on current operating performance, such as influent and effluent characteristics, flowrates, biogas production and quality. operating temperatures, etc., recordeo at each site, is summarized monthly.

5. Yearly Data Report (YEARREPORT)
   Data collected at the various sites is summarized yearly from the monthly reports.

6. Discussion Form (DISCUSS)
   Questions, comments and queries can be entered on the database by users.

TABLE 1. CANADIAN ANAEROBIC DIGESTION FACILITIES

FACILITY	LOCATION	TYPE OF OPERATION	WASTE TREATED	DIGESTER TYPE	TOPIC NAME
1. Agropur Coopérative Agro-Alimentaire	Notre-Dame-du-Bon-Conseil, Quebec	Cheese Plant	Plant Wash Water	Upflow Anaerobic Sludge Blanket	AGROPUR
2. Buteau and Tremblay Farm (CRIQ)	St. Henri-de-Levis, Quebec	Farm	Swine Manure	Fixed Film	BUTEAU
3. Cattleland Ontario Ltd.	Petersburg, Ontario	Farm	Beef Cattle Manure	Completely Mixed	CATTLELAND
4. Fallis Farm	Millbrook, Ontario	Farm	Swine Manure	Completely Mixed	FALLIS
5. Folkema Farm	Ingersoll, Ontario	Farm	Swine Manure	Fixed Film	FOLKEMA
6. Gasser Farms Ltd.	St. Pierre-de-Varennes-a-Pike-River, Quebec	Farm	Dairy Cattle Manure	Mixed Plug Flow	GASSER
7. Industrial Grain Products, a division of John Labatt Ltd.	Thunder Bay, Ontario	Wheat Starch Plant	Wheat Starch Processing Waste	Completely Mixed	GRAIN
8. Kemptville College of Agricultural Technology	Kemptville, Ontario	College Farm	Beef Cattle Manure	Completely Mixed (originally Fixed Film)	KEMPTVILLE
9. Linden Lea Farms	Cornwall, P.E.I.	Farm	Swine Manure	Completely Mixed	LINDEN
10. McCain Foods Ltd.	Florenceville, New Brunswick	Food Processing Plant	Potato Processing Waste	Anaerobic Contact Process	MCCAIN
11. Millbank Cheese and Butter Ltd.	Millbank, Ontario	Cheese Plant	Cheese Whey	Completely Mixed	MILLBANK
12. Olds College	Olds, Alberta	College Farm	Swine and Dairy Cattle Manure	Completely Mixed	OLDS
13. Pittens Farms Ltd.	Cambridge, Ontario	Farm	Dairy Cattle Manure	Completely Mixed	PITTENS
14. Selves Farms Ltd.	Fullerton, Ontario	Farm	Swine Manure	Completely Mixed	SELVES
15. University of Guelph, Arkell Research Station	Guelph, Ontario	University Farm	Swine Manure	(i) Completely Mixed (ii) Completely Mixed	GUELPH

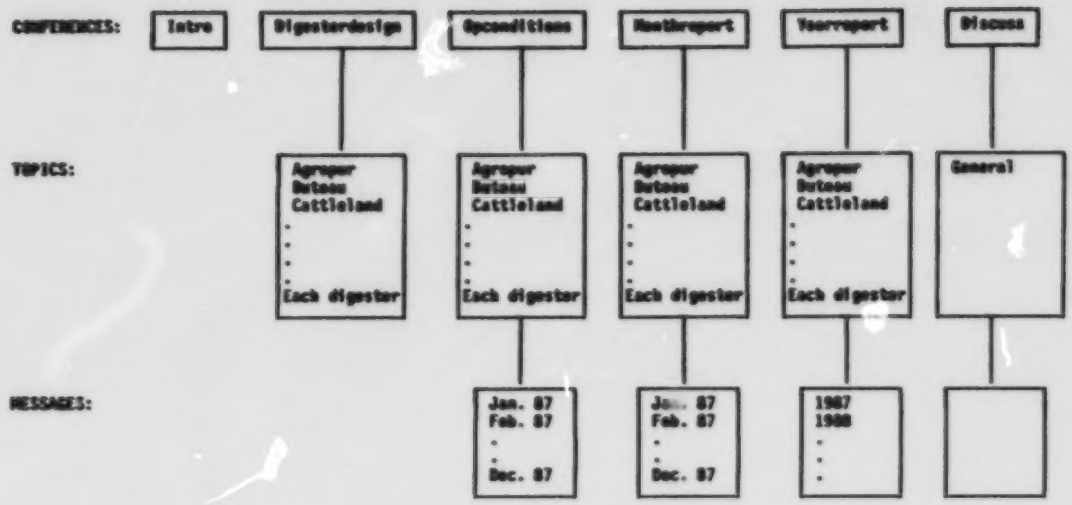

FIGURE 1 - ORGANIZATIONAL STRUCTURE FOR THE CANADIAN ANAEROBIC DIGESTION DATABASE

RESULTS AND DISCUSSION

The database is now starting its third year of operation and a number of observations have been made as follows:

- Anaerobic Technology in Canada is being used with increasing frequency in the industrial sector as a wastewater pretreatment process. The low operating cost and low sludge production from anaerobic systems has attracted the interest of most industries that have relatively high-strength wastewaters.

- In Canada most of the anaerobic treatment construction activity has been in the pulp and paper and food processing sectors. Conventional completely mixed anaerobic systems are still the most popular for the treatment of sludges from municipal plants, and there are some 130 municipal plants with anaerobic digestion facilities currently operating.

- Almost all of the anaerobic systems operating on agricultural wastes have ceased operation and no new facilities, that the author is aware of, are planned. In most cases the agricultural systems were technically successful, although most did not operate as originally predicted. The economics of producing energy on farms is not favourable and no change in the economics is predicted in the next decade. We do not anticipate any new agricultural installations in the near future.

- Four major technologies have emerged in the industrial field: the anaerobic lagoon, anaerobic contact, upflow sludge blanket, and anaerobic fixed film. The anaerobic lagoon is popular where land space is available; the upflow sludge blanket is popular for soluble high-strength wastes.

- Originally, the database was intended to be used by the owners, designers, operators and government officials to communicate information on anaerobic technology to each other. On-line participation has been extremely light since many of the people interested in anaerobic technology do not have the computer hardware and software to easily access the database. In general, computer databases and conferences are not as convenient as receiving printed information in the mail and most of the participants have indicated they would like to receive the printed information but do not need a computer log-on account.

PUBLICATIONS

A database user's manual, an interim report and two annual reports were prepared. The Canadian Applied Anaerobic Technology Data Base User's Manual describes the procedure to log on to the database and lists the computer hardware required to access the information. The interim report contains more details about the database and includes design information from each anaerobic digestion facility contained in the database. The correct citation for the interim report is: Stickney, A.R. and D.M. Prairie, Canviro Consultants. Long Term Monitoring and Database Development for Applied Anaerobic Digestion Technology in Canada. Interim Report for Contract File #51SZ.23216-5-7097. Renewable Energy Division; Energy Mines and Resources Canada, Ottawa, Ontario 1986 (111 pp). The annual reports contain a summary of the operational performance of the anaerobic digestion systems monitored during 1986 and 1987 and their current status. The first annual report (1986) also contains a state-of-the-art review of anaerobic digestion systems. Current trends and the future prospects of anaerobic digestion in the agricultural and industrial sector are also discussed. The cor-

rect citation for the 1986 annual report is: Prairie, D.M., A.R. Stickney and J.A. Barclay, Canviro Consultants. Long Term Monitoring and Database Development for Applied Anaerobic Digestion Technology in Canada. Annual Report for Contract File #51SZ.23116-5-7097. Renewable Energy Division; Energy Mines and Resources Canada, Ottawa, Ontario 1987 (51 pp).

The correct citation for the second (1987) annual report is: Barclay, J.A., A.R. Stickney and D.M. Prairie, Canviro Consultants. Long-Term Monitoring and Database Development for Applied Anaerobic Digestion Technology in Canada. Annual report for Contract file #51SZ.23283-7-6002. Renewable Energy Division, Energy Mines and Resources Canada, Ottawa, Ontario 1988 (23 pp).

Copies of the Database User's Manual, the interim report and the annual reports may be obtained through:

Renewable Energy Division
Energy, Mines and Resources Canada
580 Booth Street
Ottawa, Ontario
K1A 0E4

OR

CISTI Library
National Research Council
Bldg. M-55, Montreal Road
Ottawa, Ontario
K1A 0S2

CURRENT PRACTICES IN BIOGAS ENERGY UTILIZATION AT
MUNICIPAL WASTEWATER TREATMENT FACILITIES IN CANADA
R. E. St. Jean and A. R. Stickney
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CURRENT PRACTICES IN BIOGAS ENERGY UTILIZATION AT MUNICIPAL WASTEWATER TREATMENT FACILITIES IN CANADA

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Biogas generated by anaerobic digestion facilities at municipal water pollution control plants across Canada represents a major source of bioenergy. The objective of this project was to establish current practices and potential optimization practices for biogas production and its utilization.

A complete list of municipal anaerobic digestion systems operating in Canada was developed as part of the project. Each municipal water pollution control plant using anaerobic digestion was contacted by questionnaire and telephone. Plants with state-of-the-art digestion or biogas utilization facilities were personally visited. Special emphasis was placed on identifying the optimum approach to digester heating and mixing and biogas handling, storage, purification and use.

The information collected was catalogued using the microcomputer database system dBase III Plus. Stepwise regression analysis was performed on the data to determine the relationships between biogas production and various digester operating factors.

An expert system was developed using the microcomputer program Lotus 1-2-3 to assess various biogas utilization scenarios under different treatment plant operating conditions.

Data collected during the project indicates that municipal water pollution control plants have the potential to produce $28,000,000 of bioenergy per year, based on current natural gas prices and optimum digester operation.

Le biogaz produit dans les installations de digestion anaérobie des usines de traitement des eaux usées des municipalités au Canada constitue une importante source de bioénergie. Ce projet avait comme objectif de déterminer les méthodes actuelles de production et d'utilisation du biogaz et les façons possibles de les optimiser.

Dans le cadre du projet, on a dressé une liste complète des systèmes de digestion anaérobie exploités par les municipalités au Canada. On a fait parvenir un question- naire et on a téléphoné au responsable de chaque usine de traitement des eaux usées exploitée par une municipalité. On a personnellement effectué une visite des usines munies d'installations très perfectionnées de digestion et d'utilisation du biogaz. On a cherché de façon particulière à identifier la méthode optimale de chauffage du digesteur, de mélange des substances et de manutention, de stockage, de purification et d'utilisation du biogaz. Les données ainsi obtenues ont été cataloguées à l'aide du système de gestion des bases de données dBase III Plus utilisable sur micro-ordinateur. On a analysé les données par régression par incréments, afin de déterminer la relation entre la production de biogaz et les divers facteurs opérationnels du digesteur.

On a élaboré un système expert à l'aide du logiciel pour micro-ordinateur Lotus 1-2-3, afin d'évaluer divers scénarios d'utilisation du biogaz dans différentes conditions de traitement.

Selon les données obtenues au cours du projet, les usines de traitement des eaux usées des municipalités pourraient produire annuellement 28 millions de dollars en bioénergie, compte tenu du prix actuel du gaz naturel et en supposant que le digesteur fonctionne dans des conditions optimales.

INTRODUCTION AND BACKGROUND

Over eleven million people in Canada were served by municipal wastewater treatment plants in 1981 (Environmental Protection Service, 1981). It is projected that an additional six million Canadians will receive this service by the end of the 1980's. There are presently over 1382 municipal wastewater treatment plants in Canada, treating 60% of the domestic wastewater generated. Of the 1382 municipal treatment plants, 74 provide only primary treatment and 507 provide secondary treatment. The remainder provide treatment using lagoons, communal septic tanks and other treatment processes.

Suspended solids removals of 65-85% and BOD removals of 35-65% are achievable using primary treatment. Primary plants produce a significant quantity of sludge requiring stabilization and disposal to complete the treatment process.

In municipal systems with secondary treatment, approximately 90-95% of the suspended solids and BOD can be removed. This results in an increased amount of sludge to be treated and disposed of beyond the amount produced in primary plants.

Anaerobic digestion is used at many treatment plants in Canada to treat primary and waste activated sludges. Anaerobic digestion is a biological fermentation process in which organic matter is decomposed in the absence of oxygen. Anaerobic bacteria convert complex materials such as carbohydrates and lipids to simpler compounds which are then reduced to biogas. This biogas is dirty and wet, containing methane (65%), carbon dioxide (35%), hydrogen sulphide and other minor constituents. Biogas has an energy equivalent of about 24,210 kJ/m³ (natural gas = 37,210 kJ/m³), (Grady, 1980). The general technology of anaerobic digestion is well known and has been used for many years to treat the waste sludge generated at municipal wastewater treatment plants. The process of anaerobic digestion is widely used in Canada for the purpose of sludge volume reduction and stabilization.

Table 1 summarizes the typical quantities (grams generated/cubic meter of wastewater treated) of undigested sludge to be treated from typical primary and primary plus secondary wastewater treatment systems (Ontario Ministry of Environment, 1984).

Table 1
TYPICAL UNDIGESTED SLUDGE GENERATION RATES FOR PRIMARY AND PRIMARY PLUS SECONDARY WASTEWATER TREATMENT SYSTEMS

Wastewater Treatment Systems	Without Phosphorus Removal			With Phosphorus Removal		
	Dry (g/m³)	Volatile (%)	Volume (L/m³)	Dry (g/m³)	Volatile (%)	Volume (L/m³)
Primary	120	65	2.0	170	65	3.2
Primary + Secondary	180	65	4.0	220	60	5.0

(Ontario Ministry of Environment, 1984).

The biogas generated during the anaerobic treatment process has been used as an energy source almost since the implementation of anaerobic digestion systems at municipal plants. However, very little effort in the past has been spent in optimizing biogas production or the utilization of this renewable resource. The primary use to date has been the production of hot water or steam for process heating of the digestion units and the excess biogas is burned in a waste gas burner.

Recently, the generation and utilization of biogas from anaerobic digestion systems has received increased attention as a method of further reducing operating expenses at many municipal plants. Possible applications for biogas energy utilization include boiler fuel, stationary engine fuel, vehicle fuel, and electrical power co-generation.

In general, comprehensive methods to determine strategies for the optimum generation and utilization of municipal digester biogas are not available. The two major limitations to the effective use of biogas in Canada are thought to be:

- lack of a database and decision-making process to determine the feasibility of utilizing the biogas
- lack of appropriate strategies for biogas utilization

While biogas is already used at many municipal plants to reduce treatment process costs, it is anticipated that significant additional energy and cost savings could be achieved at many of these plants through the appropriate use of this renewable resource.

METHODOLOGY

All available documentation pertaining to Canadian wastewater treatment plants, including the "National Inventory of Municipal Waterworks and Wastewater Systems in Canada 1981" (Environmental Protection Service, 1981), and the "MUNDAT Inventory, Wastewater Facilities" (Environmental Protection Service, 1986), were reviewed in order to determine the number of municipal anaerobic digestion systems currently operating in Canada.

A questionnaire was developed to collect specific system operating data such as:

- overall wastewater treatment plant characteristics
- specific information on anaerobic digestion including digester types, numbers, volumes, organic loading, operating temperatures, heating systems, natural gas requirements, gas storage capabilities, gas metering capabilities, gas generation rates and qualities, gas use, etc.

A contact person was established at all plants using anaerobic digestion. A letter explaining the nature of the project, along with a questionnaire, was forwarded to each contact person.

Follow-up telephone calls were made to many of the plants to verify the data indicated on the questionnaires and to uncover other potentially useful information in connection with digester operation.

The information collected from the questionnaires was catalogued using the microcomputer database system dBase III Plus. Stepwise regression analysis was performed on the data to determine the relationships between biogas production and various digester operating factors such as: design plant flow, average plant flow, population served by plant, and BOD (biochemical oxygen demand) loading to the plant.

Literature dealing with the production of biogas at municipal wastewater treatment plants was reviewed and factors governing effective design and operation of anaerobic digestion systems to maximize biogas generation and optimize its use were identified. Special emphasis was placed on identifying the optimum approach to digester heating and mixing and biogas handling, storage, purification and use. Onsite inspections were carried out at plants using advanced technology for biogas utilization.

An expert system was developed using the microcomputer program Lotus 1-2-3 to assess various biogas utilization scenarios under different treatment plant operating conditions. The model was divided into three sections. Section I was designed to determine daily biogas production at a given plant. Four methods of biogas determination were included based on relationships established from questionnaire data. Section II of the model was designed to determine the digester heating requirements. Section III was designed to provide system operators with a biogas utilization strategy based on the biogas production rate calculated in Section I, the system heat requirements calculated in Section II and several energy use inputs estimated by the operators themselves.

RESULTS

One hundred and thirty two questionnaires were sent out to treatment plants identified as using anaerobic digestion in their process, and 92 replies were received. Of the questionnaires returned, 21 indicated that their anaerobic digesters were either not operating or no longer employed anaerobic digestion. Table 2 summarizes the number of systems that currently employ anaerobic digestion. Each system has been placed in an arbitrarily selected size category based on the design hydraulic capacity of the wastewater treatment plants.

Table 3 summarizes the average daily biogas production for each of the treatment plant size categories, defined in Table 2. Included in the table are the theoretical biogas production estimates based on optimum digester design and operation, for each size category. These were calculated from the volatile solids loading rate reported for each system, assuming that approximately 0.6 m³ of biogas is produced per kilogram of volatile solids added to the digester daily (WPCF and ASCE, 1977).

Table 2
CANADIAN MUNICIPAL ANAEROBIC DIGESTION SYSTEMS

Size Category	Treatment Plant Design Capacity (m^3/d)	Number of Systems with Digesters
Small	0 - 25,000	34
Medium	25,000 - 100,000	24
Large	>100,000	13
Total	-	71

Table 3
MEAN DAILY BIOGAS PRODUCTION

Size Category	Reported Daily Biogas Production (m^3/d) Mean	S.D.	n	Avg. Theoretical Biogas Production (m^3/d)
Small	457	319	18	772
Medium	2,913	1,958	22	2,965
Large	14,202	11,490	12	21,178

There are many basic practices that greatly affect biogas production. Maintaining a constant digester temperature of 30 to 38°C (mesophilic range) is generally considered optimum for municipal systems. Proper insulation of the digestion tanks is also important as it reduces heat loss and stabilizes temperature. Efficient mixing of the digester contents increases total bacterial activity, and thus biogas production, by ensuring that the bacteria come into contact with the undigested material. Table 4 summarizes the number of Canadian municipal anaerobic digestion systems surveyed which employ these practices.

Table 4
CURRENT PRACTICES IN DIGESTION

Practice	Digester	Number of Plants Employing Practice	Total Number of Systems	Percentage
Heating	Primary	71	71	100
	Secondary	7	56	13
Insulating	Primary	42	71	59
	Secondary	30	56	54
Mixing	Primary	68	71	96
	Secondary	-	56	-

Table 5 summarizes the various uses cited for the biogas produced at the plants surveyed. Seventy-five percent of the plants stated that they burned their biogas in boilers and most used the energy to heat their digestion tanks and/or control buildings. Ten percent of the plants used their biogas to fuel engine generator sets to produce heat and electricity. Uses for the electricity included load shaving and equipment operation. One plant used its biogas to burn the exhaust gas from an incinerator to control emissions and the remainder flared their biogas.

Table 5
BIOGAS UTILIZATION PRACTICES

Practice	No. of Plants	% of Total
Boiler	53	75
Boiler + Engine/Generator	7	10
Other	1	1
None	10	14
Total	71	100

CONCLUSION

The biogas generated by the anaerobic digestion facilities at municipal water pollution control plants across Canada represents a major potential source of renewable bioenergy. In most cases, biogas is used solely to heat digestion tanks and excess gas is often flared to the atmosphere. To date, no comprehensive attempt has been made to optimize biogas generation rates or biogas utilization.

Optimization of digester heating, mixing, insulation and loading has the potential of increasing Canadian biogas production from 144,000,000 m^3/yr to 226,000,000 m^3/yr. The total value of biogas at current estimated production rates is $18,000,000 and at estimated optimum production rates is $28,000,000. It is estimated that less than 60 percent of the current biogas production is actually utilized.

Optimization of gas production as well as its utilization at municipal treatment plants has the potential to significantly reduce both the costs associated with municipal wastewater treatment and Canada's consumption of non-renewable energy.

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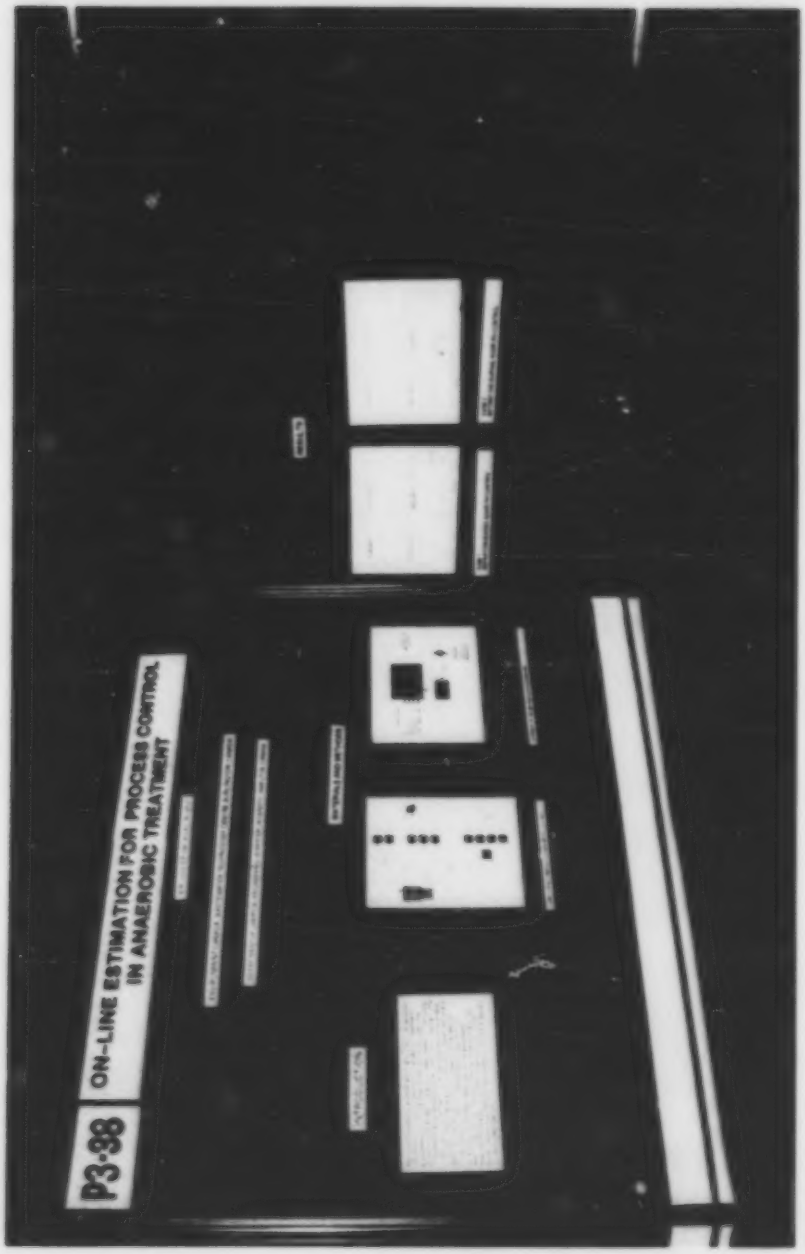
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ON-LINE ESTIMATION FOR PROCESS CONTROL
IN ANAEROBIC TREATMENT

ON LINE ESTIMATION OF VOLATILE ACIDS FOR PROCESS CONTROL IN HIGH RATE ANAEROBIC TREATMENT PROCESSES

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In anaerobic treatment processes, soluble organic compounds are converted to volatile fatty acids, such as propionic and acetic acid, by acid forming bacteria. The longer chain volatile acids such as propionic acid are converted to acetic acid by another group of bacteria and the acetic acid is converted to a methane and carbon dioxide biogas by methanogenic bacteria. Temporary overloading or toxic disturbances can cause an imbalance in the acid production and consumption steps resulting in an accumulation of volatile acids in an anaerobic reactor. Changes in the volatile acid concentration have traditionally been used as one of the main indicators of the need for corrective action.

The measurement of volatile acids is usually conducted by manual sampling followed by analysis using either titration or chromatographic techniques. Because collecting and preparing off-line samples can be expensive and labour intensive, such analyses are usually carried out only on an intermittent basis. In the more advanced high rate anaerobic process designs however, the volatile acid concentration can change quickly in response to process disturbances. Intermittent off-line sampling may not indicate a process upset until it is too late to take corrective control actions. Equipment to measure the volatile acid concentration on-line would be expensive and difficult to maintain.

To circumvent these difficulties, an on-line estimation algorithm for the volatile acid concentration has been developed. The estimator uses readily available measurements of pH, gas phase carbon dioxide concentration, temperature, and caustic addition for pH control coupled with equilibrium relationships and a simple dynamic model. The system of equations can be easily solved at any desired sampling interval. Intermittent off-line volatile acid measurements can be used to correct for measurement or modelling errors.

Lors des traitements anaérobies, des bactéries acidogènes transforment des composés organiques solubles en acides gras volatils, comme l'acide propionique et l'acide acétique. Les acides volatils présentant des chaines plus longues, comme l'acide propionique, sont transformés en acide acétique par un autre groupe de bactéries; l'acide acétique est lui-meme transformé en biogaz de méthane et de gaz carbonique par des bactéries méthanogènes. Or, une surcharge temporaire ou des perturbations toxiques peuvent causer un déséquilibre dans la production d'acide et dans les étapes de consommation, déséquilibre qui entraine l'accumulation d'acides volatils dans le réacteur anaérobie. D'habitude, on se sert des changements dans la concentration d'acides volatils comme indicateurs pour savoir s'il est nécessaire d'apporter des mesures correctives.

Normalement, pour mesurer la concentration des acides volatils, on prélève des échantillons manuellement, puis on analyse ces derniers soit par titrage, soit par chromatographe. comme le prélèvement et la préparation de tels échantillons peut se révéler couteuse et laborieuse, on ne procède a ces analyses que de facon intermittente. Toutefois, dans le cas des procédés anaérobies rapides plus perfectionnés, la concentration d'acides

volatils peut changer rapidement, en réponse à des perturbations. Un échantillonnage intermittent risque alors de ne pas mettre en évidence une perturbation avant qu'il ne soit trop tard pour prendre des mesures correctives. L'équipement nécessaire pour mesurer directement la concentration d'acides volatils serait couteux et difficile à entretenir. Pour contourner ces difficultés, on a élaboré un algorithme pour l'évaluation directe de la concentration d'acides volatils. L'évaluation se fait à partir des mesures facilement accessibles du pH, de la concentration de gaz carbonique en phase gazeuse, de la température et de l'ajout de caustique pour ajuster le pH, associées à des relations d'équilibre, et à partir d'un simple modèle dynamique. le système d'équations peut etre facilement résolu pour n'importe quel intervalle de prélèvement choisi. Des mesures intermittentes de la concentration d'acides volatils peuvent servir à effectuer des corrections pour tenir compte des erreurs de mesure ou de modélisation.

INTRODUCTION

Many of the system variables which would provide valuable information for control decisions in anaerobic treatment processes can only be determined off-line through time consuming analyses, or are only measureable on-line using instruments which are expensive or difficult to maintain. Techniques are available from process control theory which provide on-line estimates of some of these variables using available on-line measurements and a process model. In the activated sludge process, Olsson (1985) has described the development of on-line estimators for the oxygen uptake rate (OUR) and the oxygen transfer coefficient (kla), and Beck (1981) has developed on-line estimators for the concentrations of nitrifying bacterial species.

In anaerobic treatment processes, the volatile acid concentration is an example of a useful process control variable which is normally measured off-line. Soluble organic compounds are converted to volatile fatty acids by acid forming bacteria in an anaerobic system. The volatile acids are ultimately converted to a methane and carbon dioxide biogas by methanogenic bacteria. Temporary overloading or toxic disturbances can cause an imbalance in the acid production and consumption steps in an anaerobic system resulting in an accumulation of volatile acids. Changes in the volatile acid concentration have traditionally been used as one of the main indicators of the need for corrective action.

The measurement of volatile acids is usually conducted by manual sampling followed by analysis using either titration or chromatographic techniques. Because collecting and preparing off-line samples can be expensive and labour intensive, such analyses are usually carried out only on an intermittent basis. In the more advanced high rate anaerobic process designs however, the volatile acid concentration can change quickly in response to process disturbances. Intermittent off-line sampling may not indicate a process upset until it is too late to take corrective control actions.

At the Wastewater Technology Centre, an on-line estimation algorithm for volatile acids has been developed to circumvent these difficulties. The estimator uses readily available measurements of pH, gas phase carbon dioxide concentration, temperature, and caustic addition for pH control coupled with equilibrium relationships and a simple dynamic model. The system of equations is easily solved at any desired sampling interval. Intermittent off-line volatile acid measurements can be used to correct for measurement or modelling errors. The scheme is illustrated schematically in Figure 1.

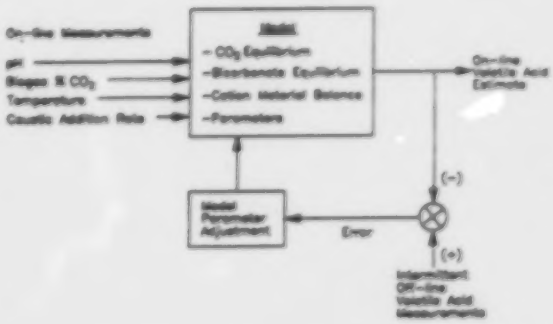

Figure 1 Schematic of an on-line estimation algorithm for volatile acids

MATERIALS AND METHODS

Data collected during dynamic experiments on a pilot scale anaerobic fluidized bed reactor were used to evaluate the performance of the estimator under actual operating conditions. The on-line data from instruments measuring pH,

biogas CO_2 concentration and temperature were collected and stored automatically using a microcomputer-based data acquisition and control system. A proportional-integral feedback controller automatically regulated the addition of 0.5 N NaOH to the reactor recycle stream as required for pH control. An automated, pre-programmed sequence of disturbances in the reactor feed was used to generate a response in the reactor effluent volatile acids. Samples were collected for off-line analysis of volatile acids by gas chromatography.

RESULTS AND CONCLUSIONS

The responses of the biogas CO_2 concentration and the reactor pH as recorded at 10 minute sampling intervals are plotted in Figure 2. The sudden changes in these variables observed during the experimental run were caused by a periodic loss of pH control due to a recurring blockage in the NaOH addition line. Temperature was maintained at a constant level of 35°C during the experiment.

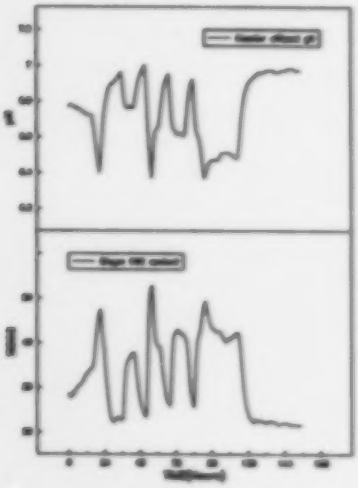

Figure 2 On-line measurements of biogas CO_2 content and pH

Figure 3 shows the results of the off-line analyses for total volatile acids as compared to the values given by the estimator. Values from the off-line measurements were fed to the estimator, as shown in Figure 1, at the beginning of the run and 48 hours after the beginning of the run. Although some noise in the estimate resulted from the pH controller problems, the agreement between estimated and measured values was generally very good.

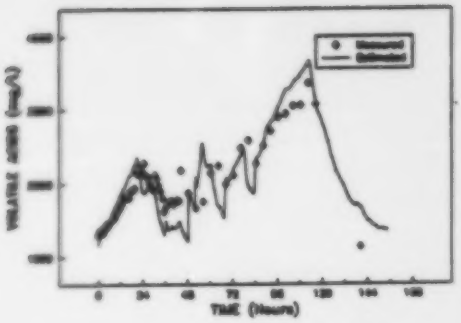

Figure 3 On-line volatile acid estimate compared to off-line analyses.

The volatile acid estimator is only one example of an on-line estimation algorithm which could be used to provide timely monitoring information, help to reduce upsets and improve the reliability of anaerobic treatment processes. Additional applications currently under investigation will utilize more measurements and more extensive process models to provide an extensive on-line picture of the operational state of an anaerobic process.

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POTENTIEL ENERGETIQUE DE LA FERMENTATION ACCELEREE ANAEROBIQUE MESOPHILE DES RESIDUS ORGANIQUES

BIOENERGIE AU CANADA

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Les problèmes économiques et écologiques posés par l'énorme production de déchets organiques tels que les fumiers liquides ou solides, les résidus végétaux et les ordures ménagères sont bien connus et, jusqu'à ce jour, ne sont pas parfaitement réglés. Notre communication a pour but d'expliquer, d'analyser et de démontrer que la filière fermentation accélérée anaérobique thermophile est une solution extrêmement valable qui permet de résoudre ces problèmes. Cela est confirmé par tous nos essais en laboratoire qui nous ont permis d'optimiser au maximum les résultats de ce genre de fermentation en augmentant le rendement énergétique qui passe ainsi de 25 à 30% pour les procédés actuellement en service, à plus de 50%.

The economic and ecological problems posed by the huge production of organic wastes such as liquid and solid animal wastes, plan residues and household refuse, are well known but have not yet been fully resolved. The intent of our paper is to explain and analyse accelerated thermophile anaerobic fermentation, and to demonstrate that it is a very good answer to these problems. This has been confirmed by all our laboratory tests, in which we have optimized the results of this type of fermentation and increased energy efficiency to over 50% from levers of 25% to 30% for the processes currently in use.

INTRODUCTION

Partout dans le monde, et cela depuis de nombreuses années, on produit du méthane par la biodégradation dans des digesteurs, des déchets organiques que nous produisons en très grande quantité.

Cette méthode de fermentation est un excellent traitement primaire des déchets organiques car elle diminue fortement leur demande en oxygène et produre de l'énergie en quantité très appréciable sous forme de gaz méthane.

La digestion anaérobie est un processus microbiologique très complexe et les paramètres qui commandent le comportement des micro-organismes sont, actuellement encore, assez mal connus car les micro-organismes, par un métabolisme très particulier, utilisent la matière organique pour produire du gaz méthane et du gaz carbonique.

Si l'on fait biodégrader la matière organique par des micro-organismes méthanogènes, on produit alors du méthane (CH^4). Une partie seulement de la matière organique est biodégradable en servant de nourriture à certaines catégories de micro-organismes.

Ainsi, en évaluant la quantité de matières organiques biodégradables contenue dans une substance, on peut évaluer la quantité potentielle de biogaz qui pourrait être produite.

Pour cela, il existe plusieurs méthodes d'essais plus ou moins compliquées et la présence d'un personnel de laboratoire très expérimenté est nécessaire à cause d'une certaine imprécision des résultats qui doit être interprétée par ce personnel.

DESCRIPTION

CHAPITRE I: DESCRIPTION SIMPLIFIEE DE LA FERMENTATION ANAEROBIE

A) Généralités

La digestion anaérobie est une fermentation bactérienne par laquelle la matière organique est dégradée en absence d'oxygène. Elle se développe par l'action combinée d'une grande variété de bactéries ayant pour habitat des cuves étanches appelées fermenteurs ou digesteurs. Ces bactéries transforment les matières organiques en biogaz composé de méthane (CH^4) de dioxyde de carbone (CO^2) et avec en plus, moins de 1% d'autres gaz tels que l'hydrogène, l'hydrogène sulfureux, l'ammoniaque, la vapeur d'eau, etc...

Une toute première population mixte de bactéries est chargée de la solubilisation des matières organiques complexes telles que la cellulose, l'amidon, les protéines... Les composés simples obtenus (sucres, acides aminés) sont les substrats essentiels de la population dite acidogène.

Ensuite, deux populations de bactéries vivent en symbiose. La première dite "acidogène", très vorace et au développement rapide, transforme les déchets organiques en substrats utilisables pour la seconde dite "méthanogène". Cette dernière, plus pacifique, aime prendre son temps pour se multiplier. C'est une bactérie philanthrope qui n'utilise que 10% de sa nourriture pour sa croissance et transforme les 90% restants en méthane.

Très bien étudié par "McKerney et Bryant" et par "Kasper et Wuhrmann", on peut dire en simplifiant, que le processus de fermentation anaérobie des matières organiques se déroule en trois (3) phases bien distinctes (tableau no. 1):

- l'hydrolyse
- l'acidogenèse
- la méthanogenèse.

Il n'existe pas de relation symbiotique entre les divers groupes de micro-organismes qui interviennent dans ce processus. Les relations sont

d'ordre trophique, c'est-à-dire qu'un groupe donné de micro-organismes profite des éléments qui lui sont fournis par le métabolisme d'autres groupes.

B) 1ere phase - hydrolyse et solubilisation

Les matières de base ou substrats sont principalement composés d'hydrates de carbone, de protéines, de lipides et de matières inorganiques. Les hydrates de carbone sont formés principalement de cellulose et de certaines parties de fibres de plantes comme l'hémicellulose et la lignine. Ces composés de fibres de plantes ne sont pas vraiment digestibles et on les retrouve dans les fumiers et les résidus de récoltes.

L'action combinée de diverses familles de bactéries anaérobies, possédant des capacités enzymatiques, protéolytiques, lipolytiques et cellulolytiques, permet la solubilisation de ces matières en réduisant les matières organiques complexes en composés organiques simples et solubles, l'activité cellulotytique est importante. La cellulose qui est formée par des unités de glucose polymérisées en chaine de longueur indéfinie comprenant des embranchements complexes est transformée par les bactéries cellulotytiques qui réduisent séquentiellement les chaines et les branches en molécules de sucres dimériques, puis en molécules de sucres monomériques qui seront ensuite transformées en acides organiques.

La transformation en simples monomères des matières premières comme la cellulose ou les matières complexes détermine une première phase dans la production de méthane. Cette première phase peut être plus longue que les autres car l'action bactérienne dans cette phase, est plus lente pour les matières complexes et les matières rapidement hydrolysées passeront à la phase suivante avant elles.

C) 2e phase - la fermentation acidogène

Les bactéries productrices d'acides pendant la phase 2, utilisent un substrat formé par les composés monomériques produits par la décomposition hydrolitique de la phase précédente et ces acides lactiques, proprioniques et acétiques, sont les produits finaux du métabolisme bactérien des hydrates de carbone.

L'acide acétique est le substrat principal pour la formation du méthane car les bactéries méthanogènes, très sélectives dans leur utilisation du substrat, sont surtout capables de l'employer.

Une petite partie des bactéries peuvent également engendrer du méthane à partir de l'hydrogène et du bioxyde de carbone produits pendant la transformation des hydrates de carbone. De même, le méthanol, un autre sous produit de la décomposition des hydrates de carbone, peut produire du méthane par réduction.

Les études sur la décomposition des substrats effectuées en 1965 par "Smith" indiquent qu'environ 70% du méthane produit, provient de l'acide acétique (méthane génération from human, animal and agricultural wastes 1971).

Le déroulement de la phase 2 n'est pas encore parfaitement expliquée à cause de sa microbiologie complexe car la flore microbienne est composée de différentes espèces de bactéries et également à cause des pourcentages des différents acides, des alcools simples, de l'hydrogène et du bioxyde de carbone.

De plus, les conditions de fermentation jouent un très grand rôle dans cette deuxième phase.

D) 3e phase - la fermentation méthanogène

Les bactéries méthanogènes sont très sélectives dans l'utilisation des différents substrats et des chercheurs (Lapp et Al) pensent que ces bactéries n'utilisent que les substrats produits surtout à la phase 2. Ainsi pour être utilisés efficacement, les composés organiques d'azote doivent être réduits en ammoniaque et ces bactéries ont besoin également, pour leurs métabolismes, de phosphate et d'autres substances dont les quantités n'ont pas été déterminées exactement mais que contiennent les fumiers ou boues liquides. Ainsi, en général, pour proliférer correctement, les bactéries méthanogènes demandent comme nourriture de la vitamine B, des acides gras et des acides aminés tels qu'ils sont fabriqués par les bactéries acidogènes de la 2e étape (Bryant et Al 1971 - Bryant 1974).

De plus, ces bactéries se reproduisent beaucoup plus lentement que les autres et sont beaucoup plus susceptibles d'être détruites par de nombreux produits y compris par les acides produits par les bactéries de la 2e phase.

Le tableau no. 4 donne, théoriquement, la composition et le volume de gaz fournis par la digestion anaérobie complète des différentes matières de base.

Au cours du processus de la fermentation anaérobie, les bactéries produisant les acides et les bactéries produisant le méthane, travaillent ensemble et il faut donc, tout au long du procédé de fermentation contrôler rigoureusement la température, l'absence d'oxygène, le taux de dilution, etc... de manière à avoir toujours le maximum de production de méthane.

D) Les températures de fermentation et leurs effets

a. Généralités

La température est la condition la plus importante qui commande la quantité de gaz méthane biologique produit. Bien que la production de gaz méthane soit possible entre 5 et 80° centigrades, les bactéries produisant le CH^4 ne vivent normalement qu'entre 20 et 70° centigrades.

Elle se classent en deux grandes catégories:

- les bactéries mésophiles, vivant entre 20 et 45°C
- les bactéries thermophiles, vivant entre 35 et 70°C

(note: les bactéries psychrophiles vivent en dessous de 25°C)

Ainsi, le choix de la température de fermentation est extrêmement important et c'est la fermentation mésophile qui est la plus couramment utilisée, soit de 30 à 40°C, et le méthane produit sert à chauffer l'effluent envoyé à fermenter.

N.B.: Contrairement à ce que l'on a pu dire

ou écrire, les variations importantes de température ne nuisent en rien aux bactéries méthanogènes, mais jouent seulement sur les constantes de vitesse.

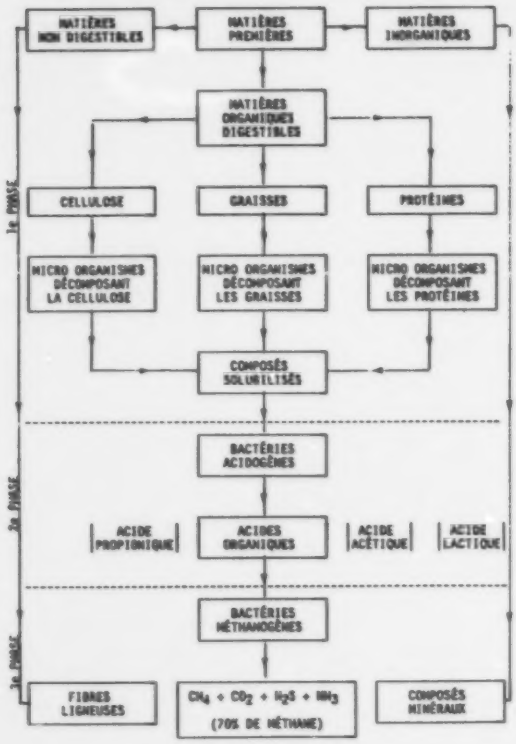
Il n'est pas utile de souligner qu'un digesteur très bien isolé thermiquement, réutilise de l'ordre de 1/12 de sa production de méthane pour son réchauffage en hiver au moment le plus froid (-30°C) en fonctionnant à 35°C.

Si l'effluent contient plus de 7 à 8% de matières organiques, il devient nécessaire d'élever la température de fonctionnement en utilisant la fermentation thermophile, soit de 50 à 60°C, mais le coût d'opération est plus élevé (Mc Carty).

Toujours d'après "Mc Carty" et d'autres chercheurs (Ghosh et Al) cette plus haute température produit presque le double de biogaz dans un temps moitié moindre, ce qui permet d'utiliser des digesteurs plus petits que pour la fermentation mésophile.

Tableau no. 1

Cycle de l'azote et du carbone pendant la fermentation anaérobie



b. Fermentation à basse température (20 à 40°C)

La température optimum étant de 35°C, le fonctionnement du réservoir de fermentation (digesteur) doit être maintenu entre 30 et 38°C. Toute variation prolongée de température (48 h. min.) entrainerait de sérieux dommages dans le cycle de la fermentation et compromettrait, à long terme, les performances de l'installation.

La dissociation anaérobie d'une molécule-gramme de glucose ne dégage qu'une faible partie de l'énergie potentielle contenue, soit environ 26 Kcal, mais le méthane produit par la fermentation anaérobie peut être utilisé comme carburant (Pfeffer 1974).

La fermentation anaérobie, en ne produisant qu'un peu de chaleur, présente quelques inconvénients pour le traitement des substances contaminées et des excréta, car la salubrité publique exige la destruction des parasites et des germes pathogènes. Ceux-ci disparaissent à la longue de la masse organique à cause des mauvaises conditions du milieu et de certains antagonismes biologiques, mais il faut conserver la masse organique en fermentation pendant une période de 15 à 20 jours pour détruire les parasites pathogènes les plus résistants transmis par les matières fécales (oeufs d'Ascaris).

c. Fermentation à haute température (40 à 70°C)

Pour cette fermentation à haute température, l'optimum se situe vers 60°C et la température du digesteur doit être maintenue entre 57 et 62°C. Dans ce cas, les variations de température sont plus dangereuses que dans la fermentation à basse température et ce paramètre doit être parfaitement contrôlé (Buhr et Andrews 1977).

Cette fermentation anaérobie à haute température présente moins d'inconvénients que la précédente car les parasites et germes pathogènes sont parfaitement détruits au bout de 8 à 10 jours de fermentation (oeufs d'ascaris).

d. Flore microbienne contenue dans les déchets organiques

Les nombreuses analyses effectuées ont démontré que les germes pathogènes et parasites courants étaient parfaitement détruits au bout de 20 jours pour la fermentation à 35°C et au bout de 10 jours pour la fermentation à 60°C (Davies A.B. 1959), (Jansen J. et Kunst 1953).

e. Délais et températures nécessaires pour la destruction des principaux micro-organismes

Tableau no. 2

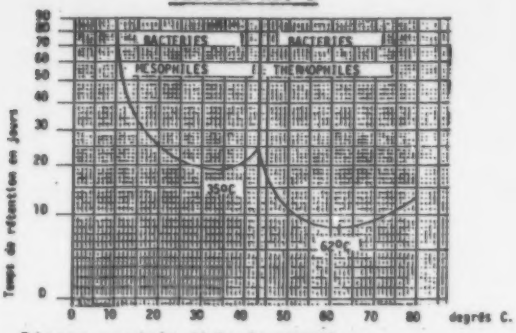
note: 60°C = 140°F

	TEMP. (°F)	TEMPS (min.)	TEMP. (°F)	TEMPS (min.)
Angillules et leurs oeufs	131	40	140	20
Ankylostomes et leurs oeufs	140	60	154	15
Ascaris Lumbricoides (oeufs)	122	60	-	-
Brucella Abortus ou B'	144-145	3	131	60
Corynobacterium Diphtariae	131	45	-	-
Entamoeba Histolytica (Kystes)	113	1-2	131	1
Escherichia Coli	131	60	140	20
Necator Americanus	113	50	-	-
Micrococcus Pyogenes Var. Aureus	122	10	-	-
Mycobacterium Tuberc. Var. Hominis	151	15-20	152,6	2-5
Paratyphus B.	131	60	140	20
Salmonella Sp.	131	60	140	15-20
Salmonella Typhosa	131-140	30	140	20
Shigella Sp.	131	60	-	-
Streptococcus Pyogenes	129	10	-	-
Taenia Saginata	131	1-2	-	-
Trichinella spiralis larvae	131	1	140	0

(Gotaas 1956)

f. Influence de la température sur le temps de digestion anaérobie

Tableau no. 3



g. Biogaz produit théoriquement

"Engineering Digest" dans son édition de novembre 1974, a présenté une étude très complète avec le tableau ci-après sur la composition et le volume de gaz produit par une digestion anaérobie théoriquement complète des différentes matières de base (anaerobic treatment processes and methane production).

La quantité et la composition du gaz de digesteur produit dans une dégradation complète dépendent de la composition des déchets et peut être déterminées par la formule de BUSWELL:

$$C_nH_aO_b + (n - a/4 - b/2)\ H_2O - (N/2 - a/8 - b/4)\ CO_2 + (n/2 - a/8 - b/4)\ CH_4$$

De cette formule on peut déduire que lorsque $n > a/4 + b/2$, l'eau est utilisée dans la réaction et le poids du gaz produit excède alors le poids sec de la matière organique dégradée.

Si la formule de BUSWELL est appliquée aux différentes classes principales de matières organiques, on obtient les valeurs du tableau ci-dessous:

Tableau no. 4

Matières de base	Composition en %				Volume de gaz produit par 1 kg de matières digestibles			
	en poids		en volume		biogaz		méthane	
	CO_2	CH_4	CO_2	CH_4	m^3	pi^3	m^3	pi^3
Hydrates de carbone $C_6H_{12}O_6$	73	27	50	50	0,75	26,3	0,37	13,15
Lipides $C_{50}H_{90}O_6$	52	48	28	72	1,44	50,9	1,04	36,6
Protéines $NC_2H_{4,3}H_2O$	73	27	50	50	0,98	34,6	0,49	17,3

CHAPITRE II: ESSAIS EN LABORATOIRE

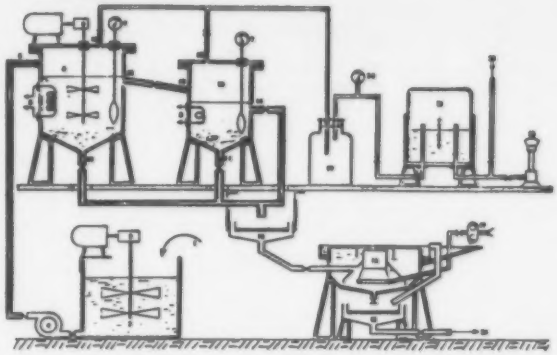
A) Historique

Etant concepteur d'un procédé de biométhanisation des liquides organiques, j'ai commencé les premiers essais à titre de recherches personnelles en 1970. Ces essais furent réalisés dans mon atelier transformé en laboratoire.

Après la prise de brevets et les essais terminés en 1985, le laboratoire fut démantelé entièrement.

Les essais permirent l'étude de la fermentation anaérobie du lizier, du fumier de vaches, des excréments humains, des débris végétaux et des ordures ménagères broyées.

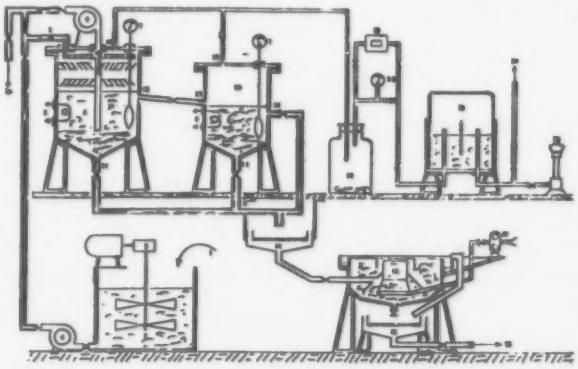
B) Fermentation anaérobie, mésophile et thermophile des fumiers liquides procédé avec digesteurs conventionnels



1) Arrivée - lizier et eau
2) Cuve de dilution
3) Brasseur - 2 t/m
4) Pompe - 1,4 cm^3/m à 0,5 cm^3/m
5) Alimentation digesteur primaire
6) Digesteur primaire - V.U.=16 l
7) Contrôle du chauffage - 20/70 °C
8) Chauffage 24 V. C.A.
9) Brasseur - 6 t/m
10) Digesteur secondaire - V.U.=8 l
11) Sortie des boues digérées
12) Sortie digesteur primaire
13) Alimentation digesteur secondaire
14) Sortie digesteur secondaire
15) Filtres type multipores
16) Décanteur-floculateur - V.U.=6 l
17) Surpresseur d'air - 5 l/h
18) Sorties du biogaz
19) Déshydrateur
20) Pression du biogaz - 0/20 gr
21) Gazomètre - V.U.=25 l - 15 gr/cm^2
22) Bruleur
23) Analyse du biogaz
24) Analyse de l'eau épurée

C) Fermentation anaérobie, mésophile et thermophile des fumiers liquides, procédé avec surfaces fixes de ruissellement

Installation identique à la précédente mais avec le digesteur primaire contenant des surfaces fixes de ruissellement.



1) Arrivée - déchets et eau
2) Cuve de dilution
3) Brasseur - 2 t/m
4) Pompe - 2 cm^3/m
5) Alimentation digesteur primaire
6) Digesteur primaire - V.V.=16 l
7) Contrôle du chauffage - 20/70 °C
8) Chauffage 24 V. C.A.
9) Brasseur - 6 t/m
10) Digesteur secondaire - V.V.= 10 l
11) Sortie des boues digérées
12) Sortie digesteur primaire
13) Alimentation digesteur secondaire
14) Sortie digesteur secondaire
15) Filtres type multipores
16) Décanteur-floculateur - V.V.=9 l
17) Surpresseur d'air - 6 l/h
18) Sorties du biogaz
19) Déshydrateur
20) Pression du biogaz - 0/20 gr
21) Gazomètre - V.V.=25 l - 15 gr/cm^2
22) Débitmètre pour biogaz - 15 l/h
23) Bruleur
24) Analyse du biogaz
25) Analyse de l'eau épurée
26) Analyse des échantillons

RESULTATS

CHAPITRE III: ESSAIS EN LABORATOIRE AVEC LES ORDURES MENAGERES BROYEES

A) Données de base

Composition des ordures ménagères et analyse

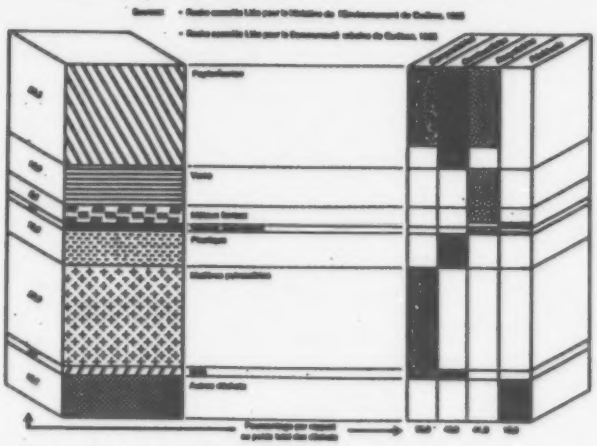
Les caractéristiques quantitatives et qualitatives des ordures ménagères sont très variables. Elles dépendent de la situation géographique, du niveau de vie de la population, de la saison, de l'année, etc...

Les ordures ménagères contiennent de 40 à 65% de matières organiques putrescibles dont les 3/4 sont facilement biodégradables.

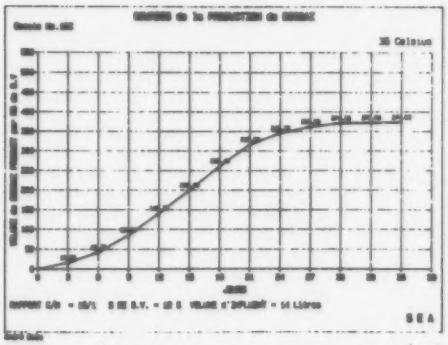
Le tableau no. 5 reprend une composition typique des ordures ménagères, les % étant exprimés sur une base de matières sèches.

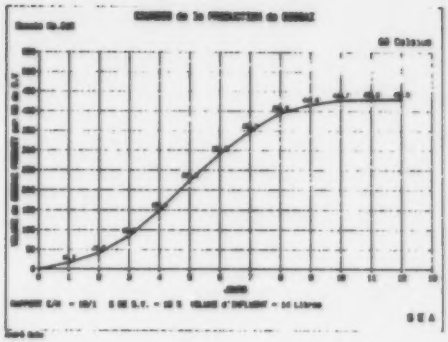
Tableau no. 5

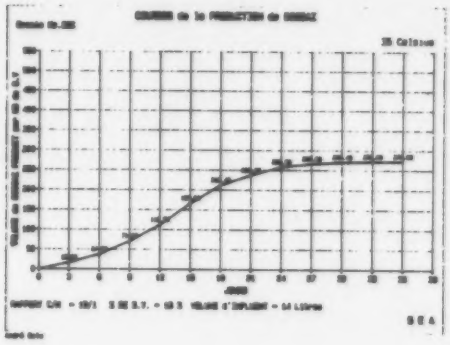
Composition et caractéristiques des déchets solides municipaux au Québec

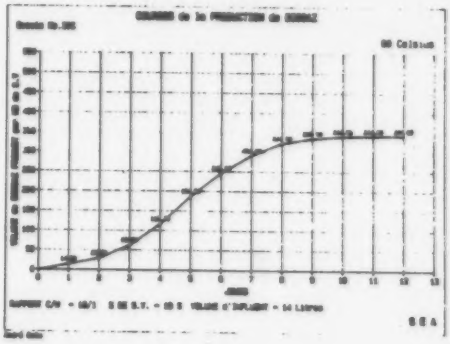


B) Résultats d'essais









CONCLUSION

L'avenir de la fermentation méthanique

La fermentation méthanique est appliquée depuis plus de 50 ans dans le traitement des boues de station d'épuration. Dans ce cas, elle fait appel aux espèces bactériennes mésophiles se développant naturellement dans de grands fermenteurs ou digesteurs infiniment brassés par des moyens mécaniques ou par injection de gaz; l'alimentation est continue. Les temps de rétention hydrauliques sont importants et dépassent généralement 12 à 15 jours.

La recherche en technologie des digesteurs a donc abouti à de nombreuses réalisations, ces dernières années, et elle a progressé de façon inté-

ressante. Car, il faut bien reconnaître que sur le marché des effluents d'élevage, le plus important par le potentiel de production d'énergie, des procédés fiables testés suffisamment longtemps en vraie grandeur, ont été proposés. Il est ainsi permis d'être très optimiste dans le domaine du traitement des effluents polluants liquides où les techniques en cours de mise au point paraissent suffisamment simples à mettre en oeuvre pour être fiables à long terme, et surtout économiquement rentables en permettant, en outre, de dépolluer en produisant de l'énergie plutôt que de fournir de l'énergie pour dépolluer.

Le rendement de transformation de la matière organique par méthanisation peut atteindre 80 à 90% lorsque cette matière est constituée par des protéines et des hydrates de carbone simples, à l'état soluble ou colloïdal. Il tombe à 50% ou moins lorsque la matière organique est plus complexe et riche en composés ligno-cellulosiques ou en lipides.

Les deux problèmes qui se posent industriellement sont donc:

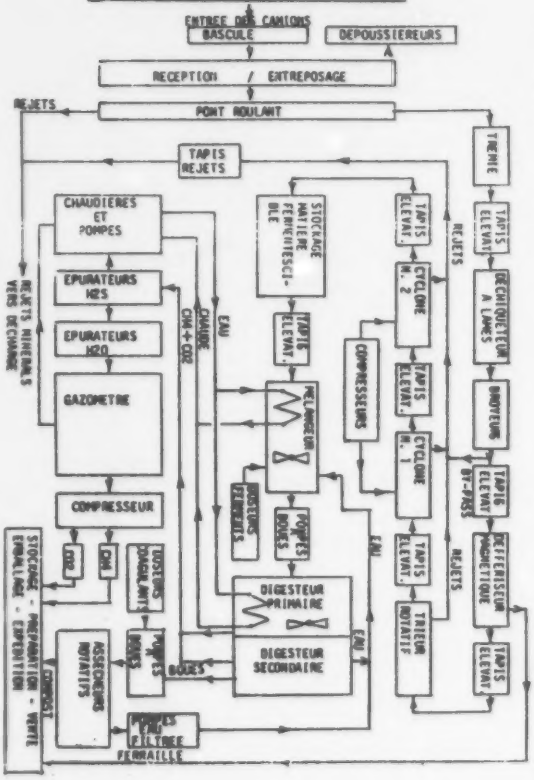
- Intensifier le processus pour réduire la taille des installations;
- améliorer les rendements d'hydrolyse et d'acidification pour accroître la part méthanisable dans le substrat, et par conséquent, accroître la production de gaz et réduire la pollution résiduelle.

En conséquence, les recherches actuelles doivent porter sur:

- Une meilleure connaissance des phases intermédiaires de la biothimie du procédé pour mieux le conduire, le modéliser et donc le rendre plus fiable;
- une meilleure connaissance des bactéries impliquées dans le processus pour aboutir peut-être à l'emploi de souches sélectionnées;
- l'étude des possibilités d'utilisation de groupes bactériens différents, soit plus performants: bactéries thermogènes et thermophiles, soit permettant d'ouvrir le champ d'application de la méthanisation sans en obérer le bilan thermique; bactéries psychrophiles;
- une meilleure mise en oeuvre du système: intérêt de la séparation du processus fermentaire en plusieurs phases; accroissement des quantités de biomasse active par unité de volume de fermenteur, soit par concentration physique améliorée (flottation, ultrafiltration au lieu de la décantation statique de la culture bactérienne recyclée) soit, en utilisant des réacteurs à bactéries fixées qui pourraient être particulièrement intéressants pour le traitement d'effluents plus dilués en s'affranchissant des difficultés de séparation liquide solide qui sont difficiles à résoudre dans les systèmes à cultures libres.

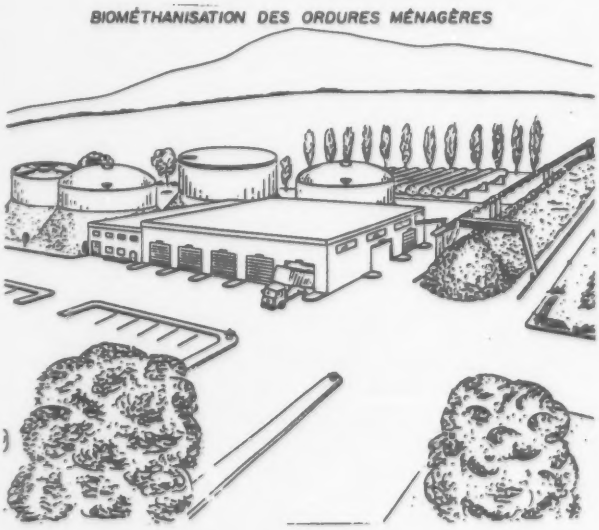
D'une façon générale il faut remarquer que la biologie ne représente qu'une part infime de l'effort entrepris dans ce domaine, puisque l'on use toujours de l'approche de type "boite noire" de manière tout à fait macroscopique et souvent insuffisante.

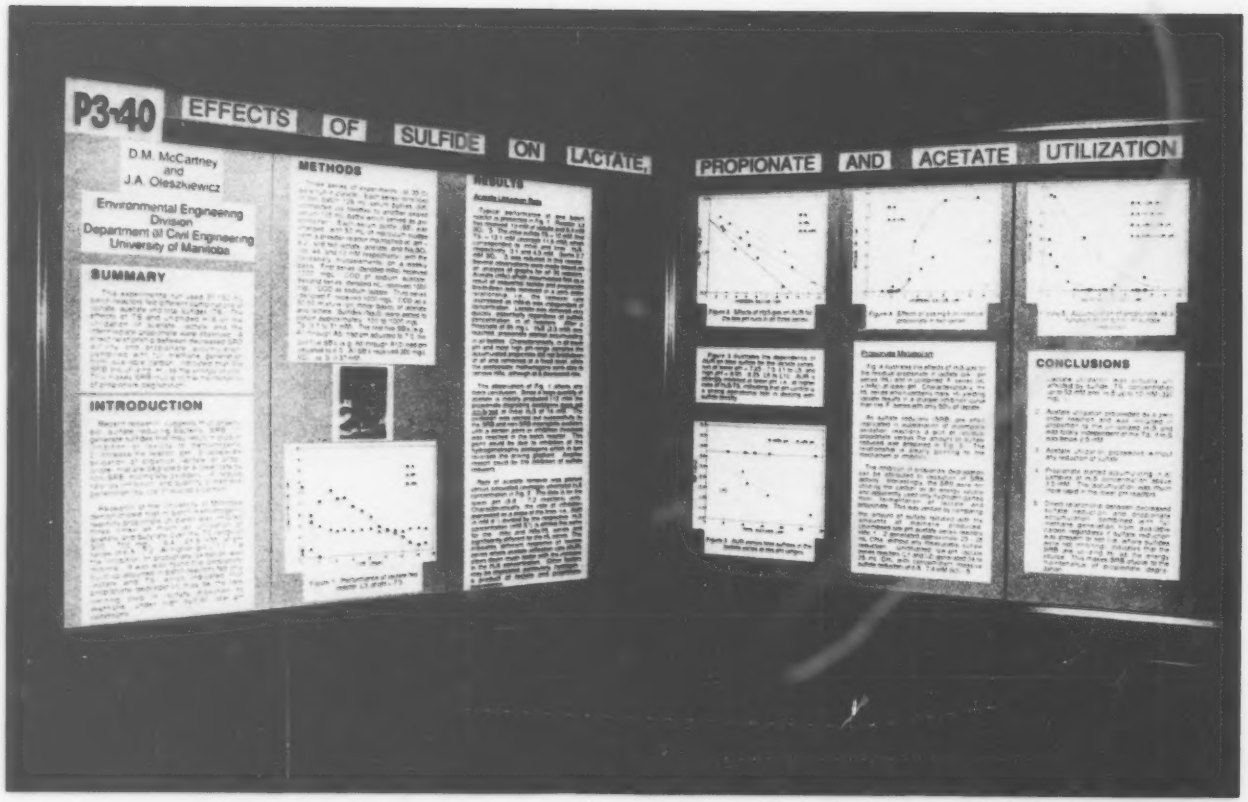
SCHEMA DE PRINCIPE D'UNE FUTURE USINE DE TRAITEMENT DES ORDURES MENAGERES PAR TRANSFORMATION EN BIOGAZ



FUTURE USINE

BIOMÉTHANISATION DES ORDURES MÉNAGÈRES




P3-40
EFFECTS OF SULFIDE ON LACTATE, PROPIONATE AND ACETATE UTILIZATION
D.M. McCartney
and
J.A. Oleszkiewicz
Environmental Engineering Division
Department of Civil Engineering
University of Manitoba
SUMMARY
INTRODUCTION
METHODS
RESULTS
CONCLUSIONS

EFFECTS OF SULFIDE ON LACTATE, PROPIONATE AND ACETATE UTILIZATION

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During anaerobic wastewater treatment, a reduced percentage of methane yield may result when high sulfate concentrations are present. Acetoclastic sulfate reducing bacteria (SRB), that reduce sulfate to sulfide, use substrate that would have otherwise been converted to methane by methane producing bacteria (MPB). Therefore, operational and environmental conditions which favour MPB over SRB would increase the methane yield per unit of substrate.

Research conducted at the UM found that in found that in methanogenic batch reactors propionate utilization was inhibited three times as much as acetate and butyrate utilization over the TS range of 300-700 mgL^{-1} at a pH range of 6.5 - 7.2. It was also found that propionate build-up occurred in batch reactors fed only lactate which indicated propionate utilization to be the rate limiting step in lactate breakdown under high sulfide conditions.

An experimental run, now in progress, is studying the effects of TS and H_2S on the utilization of acetate, butyrate and a combination of both substrates by SRB and MPB. The results of this study, will be included in the paper.

Au cours du traitement anaérobie des eaux usées, le pourcentage de méthane produit peut être réduit si les concentrations de sulfate song élevées. Les bactéries acétoclastiques le sulfate en sulfure (BRS) utilisent le substrat qui aurait autrement été transformé en méthane par des bactéries productrices de méthane (BPM). Par conséquent, les conditions opérationnelles et environnementales qui favorisentles BPM par rapport aux BRS ferait accroître le rendement de méthane par unité de substrat.

Recherches effectuées à l'UM ont montré que dans les réacteurs méthanogès discontinus, l'utilisation du propionate était trois fois plus inhibée que l'utilisation de l'acétate et du butyrate lorsque la concentration de ST variait de 300 à 700 $mg.L^{-1}$, le pH variant de 6,5 à 7,2 (Figures 1 à 4). On a également constaté qu'il y avait accumulation du propionate dans les réacteurs discontinus alimentés uniquement avec du lactate, ce qui montre que l'utilisation du propionate est bien l'étape qui limite la vitesse de la dégradation du lactate en présence de concentrations élevées de sulfure.

Une expérience en cours vise à édudier les effets du ST et du H_2S sur l'utilisation de l'acétate, du butyrate et d'une combinaison des deux substrats par les BRS et les BPM. Les résultats de cette expérience seront indiqués dans la communication.

INTRODUCTION

Anaerobic sulfate reducing bacteria (SRB) use sulfite or sulfate as terminal electron acceptors. Recent research (1, 2, 3) suggests that in the process, SRB: 1) generate sulfides that may result in product inhibition or toxicity to methanogens; 2) increase the reactor pH; 3) accelerate oxidation of organics (lactate or propionate) that are degraded at a lower rate by non-SRB incomplete oxidizers; 4) reduce rate (by inhibition) and quantity of methane generation (by use of available carbon).

Research conducted at the University of Manitoba (UM) (3) has shown that SRB are more sensitive to relatively high total sulfide (TS) concentrations than methane producing bacteria (MPB), while both are sensitive to relatively high H_2S concentrations. Therefore, at relatively high TS and high pH the MPB should be able to outcompete the SRB for substrate, by virtue of the lower inhibition TS threshold evidenced by SRB. The most recent research at UM demonstrated (5) that in batch methanogenic reactors propionate utilization was inhibited three times as much as utilization of acetate and butyrate over the TS range of 300 - 700 mgL^{-1} (9.4 - 21.8 mM) at pH range of 6.5 - 7.2. At higher pH = 7.7 - 7.8 the inhibition of propionate oxidation was minimal. It was also found that propionate build-up occurred in batch reactors fed only lactate and TS, which indicated that propionate degradation may be the rate limiting step in lactate digestion to methane, under high sulfide, low pH conditions.

This presentation addresses the question of inhibition of methanogenic and sulfate reducing bacteria by sulfide, at different concentrations and at two pH levels, treating two simple organics: lactate and acetate. Two pH levels were chosen to cause various ratios of unionized sulfide (gaseous H_2S) to total sulfide (TS).

METHODS

Three series of experiments (at 35°C) were run in parallel. Each series consisted of ten batch 125 mL serum bottles connected via needles to another sealed serum 125 mL bottle which served as gas container. This was done to avoid venting the H_2S gas and thus maintaining constant sulfide level in the liquid.

Gas production was determined by means of a previously calibrated pressure transducer. Each serum bottle was charged with 50 mL of inocculum sludge from a breeder reactor maintained at pH = 8.2 and fed lactate, acetate, 1800 mg/L Na_2SO_4, with the necessary microelements, on a weekly basis. First series (denoted HAc) received 1000 mgL^{-1} COD of sodium acetate. Second series (denoted HL) received 1000 mgL^{-1} COD

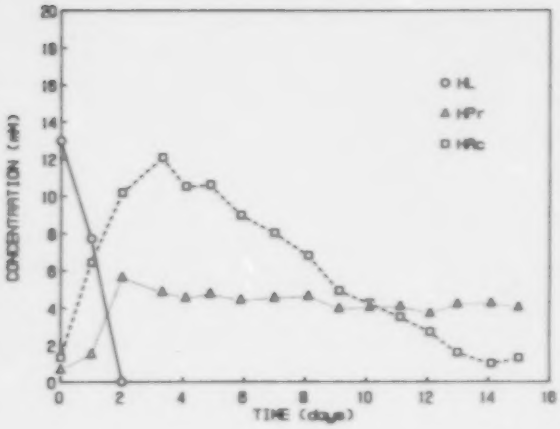

Figure 1. Performance of lactate fed reactor L3, at pH = 7.3.

oxidation was carried out successfully by the SRB and non-SRB incomplete oxidizers until a certain point or inhibition threshold was reached in the batch reactor. This point could be due to inhibition of the hydrogenotrophic acetogens responsible for reaction 3, which in turn reverses the driving gradient.

Another reason could be the inhibition of sulfate reducers responsible for reaction 4, energetically very favorable at ΔG^{01} = -151 kJ per reaction (6):

$$4CH_3CH_2COO^- + 3SO_4^{2-} \rightarrow 4CH_3COO^- + 4HCO_3^- + + 3HS^- + H^+ \quad (4)$$

The suspected accumulation of H_2 (not measured here) could also indicate inhibition of the hydrogen/CO_2 synthesizing methanogens.

Rate of acetate removal, calculated as the best fit slope of the acetate (decreasing) concentration curve was plotted versus calculated (average) unionized H_2S concentration in Fig. 2. The data is for the lower pH (6.8 - 7.2 reactors) only. Characteristically, the rate of inhibition expressed as a slope of the lines (i.e., AUR in mM d^{-1}) divided by the respective H_2S concentration (mM S^{-2}) is almost the same for the HAc and HAc/HL series and significantly different for the HL series. This indicates different response of lactate series where acetate utilization rate (AUR) slows down much faster with the increase in the H_2S concentration. The starting concentration of acetate were HAc 21 mM, HL/HAc 18 mM and HL 12 mM. However, the AUR should have been similar as the removal rate was zero order, i.e., independent of concentration. Other factors may be implicated, particularly hydrogen - a product of lactate and propionate degradation.

Figure 3 illustrates the dependence of AUR on total sulfide for the lactate series-run at lower pH = 7.25 - 7.5 L1 to L5 and high pH = 8.05 - 8.25 L6 to L10. It follows that at higher pH total sulfides have virtually no effect on the rate of acetate utilization. AUR is strongly inhibited at lower pH, i.e., at

as sodium lactate. Third series (denoted F) received 1000 mgL^{-1} COD as a 50/50 mixture (on molar basis) of acetate and lactate. Sulfides (Na_2S) were added to obtain approximately 100 to 1000 mgL^{-1} - TS (3.1 to 31 mM). The first five bottles (e.g., A1 through A5) had pH adjusted to 7.0, the last five bottles (e.g. A6 through A10) had pH adjusted to 8.0. All bottles received 300 mg/L SO_4^{2-} as S (9.37 mM).

Analyses

Microsyringes were used for sample collection. Gow-Mac gas chromatograph equipped with FID was used for analyses of acetate and propionate. Waters high pressure liquid chromatograph equipped with UV variable wavelength detectors set at 210 mm was used for lactate determination.

Data Interpretation

Total sulfides and pH changed slightly (0.05 - 0.1 unit) during incubation due to sulfate reduction and concomittant generation of alkalinity. For data interpretation arithmetic averages of pH, TS and H_2S concentrations were reported. H_2S content was calculated based on the ionization equation $H_2S \rightleftarrows HS^- \rightleftarrows S^{-1}$, from actually measured pH values. TS were measured after the serum bottle was sealed at start-up and at the end of incubation.

The average H_2S and TS reported here was often less than half of the final recorded sulfide concentration. The following expressions of conversion of intermediary metabolite acetate equivalents were assumed after Moletta et al. (7):

Lactate: $3\,CH_3CHOHCOO^- \rightarrow 2CH_3CH_2COO^- + CH_3COO^- + HCO_3^- + H^+$; 1.5 mol HAc mol^{-1} HL (1)

Propionate: $CH_3CH_2COO^- + 3H_2O \rightarrow HCO_3^- + H^+ + 3H_2$; 1.75 mol HAc mol^{-1} HPr (2)

Dihydrogen: $4H_2 + 2CO_3^- + H^+ \rightarrow CH_3COO^- + 4H_2O$; 0.25 mol HAc mol^{-1} H_2 (3)

RESULTS

Acetate Utilization Rate

Typical performance of one batch reactor is presented in Fig. 1. Reactor L3 has received 13 mM of lactate and 9.4 mM SO_4 - S. The initial sulfide TS_i = 10 mM, final TS_f = 13.1 mM (average 11.6 mM) which corresponded to initial and final H_2S, respectively 3.1 and 4.3 mM. Some 2.7 mM SO_4 - S was reduced in this reactor. Several observations were made based on an analysis of graphs for all 30 reactors. Acetate (HAc) which accumulated first as a result of sequential lactate and propionate breakdown was removed in a zero order relationship, i.e., the removal rate (expressed as mM/d) was independent of concentration. Lactate was removed very quickly, essentially regardless of sulfide concentration, in all reactors. After a threshold of 80 mg L^{-1} H_2S (2.5 mM) was reached, propionate started accumulating in all bottles. Characteristically, in all lower pH and most high pH-range samples the accumulated propionate did not breakdown at all and remained at a fixed level, while the acetoclastic methanogens were able to remove HAc, although at a decreased rate.

The observation of Fig. 1 allows one more conclusion. Since a large quantity of acetate is initially produced (12 mM) the propionate degrading acetogens were not inhibited at initial H_2S of 10 mM, i.e., both reaction eq. 1 and 2 were completed. The

higher ratio of H_2S/TS, indicating that pH control is a strong operational tool in dealing with sulfide toxicity.

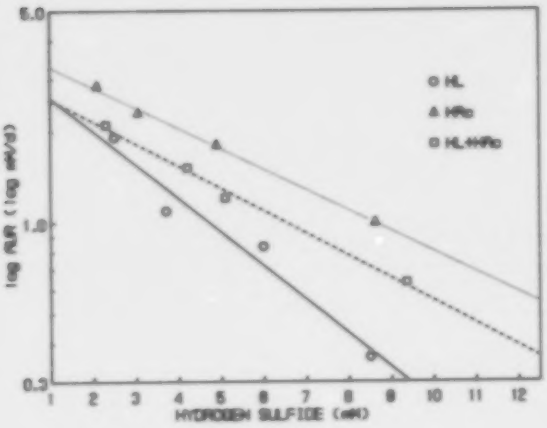

Figure 2. Effects of H_2S gas on AUR for the low pH runs in all three series.

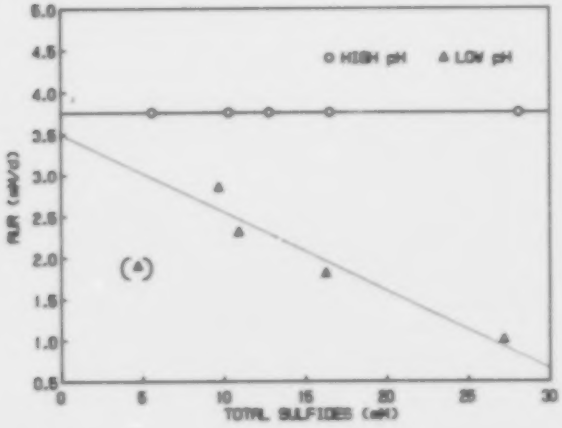

Figure 3. AUR versus total sulfides in the lactate series at two pH ranges.

Propionate Metabolism

The inhibition of propionate utilizing organism is the most frequently noted phenomenon. As shown by Wiegant et al. (8) propionate utilizers have extremely slow growth rate and are very sensitive to the increase of H_2 (metabolite - eq. 2) thus are dependent on at least two other groups of bacteria. Complex substrate will generate more H_2 (e.g. lactate in eq. 1) thus propionate slows up first in any digester upset. Fig. 4 illustrates the effects of H_2S gas on the residual propionate in lactate low - pH series (HL) and in combined F series (HL + HAc) at lower pH. Characteristically, the HL series which contains more H_2 yielding lactate results in a sharper inhibition curve than the F series with only 50% of lactate.

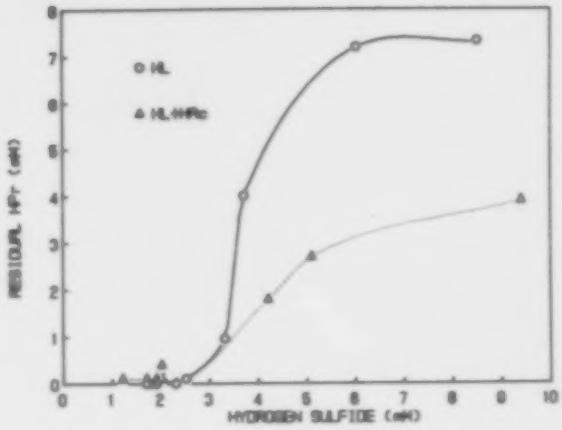

Figure 4. Effects of gas H_2S on residual propionate in two series.

As sulfate reducers (SRB) are often implicated (1) in acceleration of incomplete oxidation reactions (e.g. equation 4) a plot of residual propionate versus the amount of sulfate reduced was prepared in Fig. 5. The relationship is clearly pointing to the mechanism of inhibition.

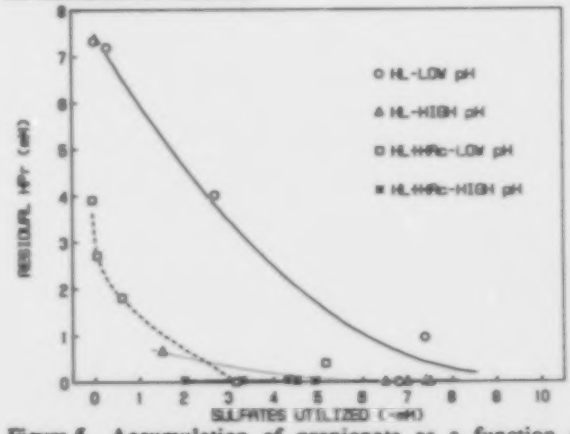

Figure 5. Accumulation of propionate as a function of inhibition of sulfate reduction.

The inhibition of propionate degradation can be attributed to cessation of SRB activity. Interestingly, the SRB were not utilizing the carbon as an energy source and apparently used only hydrogen gained from fermentation of lactate and propionate. This was verified by comparing the amount of sulfate reduced with the amounts of methane produced. Uninhibited low-pH acetate series reactors HAc 1 - 2 generated approximate 23 - 28 mL CH_4, without any measurable sulfate reduction. Uninhibited low-pH lactate series reactors (L1 and L2) generated 24 to 26 mL CH_4 with concomittant massive sulfate reduction of 6.8 - 7.4 mM SO_4 - S.

One can conclude that the deteriorated propionate degradation may be the result of cessation of sulfate reduction capabilities of SRB which were the most effective hydrogen scavengers in this mixed culture system.

CONCLUSIONS

1. Lactate utilization was virtually unaffected by sulfide (TS) concentration up to 33 mM and H_2S up to 10 mM (320 mgL^{-1}).

2. Acetate utilization proceeded as a zero order reaction and was inhibited in proportion to the un-ionized H_2S and was totally independent of the TS, if H_2S was below 2.5 mM.

3. Acetate utilization proceeded without any reduction of sulfate.

4. Propionate started accumulating in all samples at H_2S concentration above 3.5 mM. The accumulation was much more rapid in the lower pH reactors.

5. Direct relationship between decreased sulfate reduction and propionate accumulation, combined with full methane generation from available carbon regardless if sulfate reduction was present or not (i.e. where sulfides were not inhibiting), indicates that the SRB are utilizing H_2 as the energy source. This makes SRB crucial to the maintenance of propionate degradation.

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P3-41

THE FORM AND COMPOSITION OF GRANULES FROM UASB REACTORS

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Anaerobic granular sludge provided by Paques-Lavalin was investigated after 134 days of operation in a bench scale 20 L reactor fed with artificial feed containing volatile fatty acids.
All granules, originally received, had a uniform dark (almost black) colour. About 60 days after start-up of the reactors, the dark granules differentiated into white, grey and black. Scanning Electron Microscopy (SEM) and Energy Dispersive Analysis of X-Rays (EDAX) were performed on these forms of granules. Different regions in the granules and the differences in elemental composition were thus documented.
The observed granules differed also in their physical properties. The black granules were firm and quite resistant to mechanical stresses, while the white granules were very delicate and relatively easy to destroy. In terms of microbial population, no difference was observed in these three forms of granules.

On a étudié une boue granulaire anaérobie fournie par la société Paques-Lavalin, après un traitement de 134 jours dans un réacteur de laboratoire d'une capacité de 20 L alimenté avec une charge artificielle contenant des acides gras volatils. Dans leur état initial de réception, tous les granules présentaient une couleur uniforme foncée (presque noire). Quelque 60 jours après la mise en marche des réacteurs, les granules noires se transformaient en granules de couleur blanche, grise et noire. Ces trois types de granules ont été examinés par microscopie électronique balayage (SEM), et par analyse aux rayons X énergie dispersive (EDAX). On a ainsi pu étudier différentes régions des granules et déterminer les différences de composition élémentaire de ces régions.
Les granules examinés présentaient également différentes propriétés physiques. Les granules noirs étaient fermes et résistaient trés bien aux contraintes mécaniques, tandis que les granules blancs étaient très délicats et des contraintes relativement faibles appliquées en cisaillement suffisaient les détruire. Aucune différence n'a été observée chez ces trois types de granules en termes de leur population microbienne.

INTRODUCTION

The aggregation of anaerobic sludge and granule formation at selected values of process parameters has been confirmed by a number of authors [1], [2], [3], [4], and this phenomenon has been already used in several industrial applications [5], [6].

Low influent COD concentration, and low upflow velocities within the reactor are reported as the most important parameters that initiate the aggregation of microorganisms into granular form. Such granules are able to withstand a continuous organic loading rate of up to 1.6 g COD/g VSS/d [7], with an upflow velocity of up to 1.5 m/h [8]. However, both of these parameters influence the form and composition of the granules.

The granules studied in this work were taken from a UASB reactor operated at a moderate loading rate of 0.6 g COD/g VSS, and medium upflow velocity of 0.5 m/h. A high calcium concentration of 100 mg/l was used in the influent stream.

METHODOLOGY

Reactor

A 20 litre reactor was used with continuous flow operation (Figure 1).

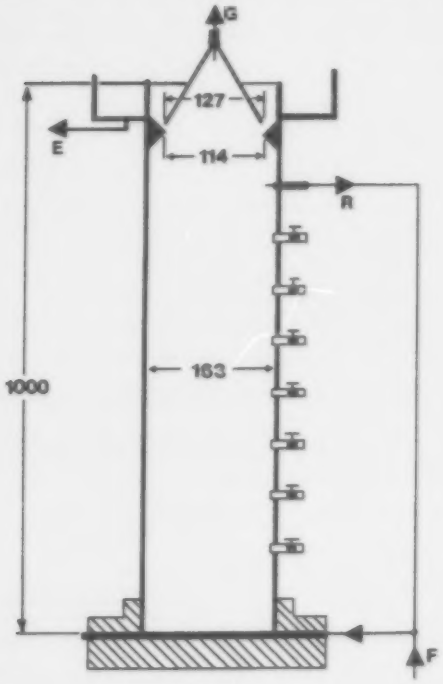

Figure 1 The UASB Reactor

Granules

The granules were provided by Paques-Lavalin, and had previously been used in a pilot plant reactor treating pulp mill wastes at Domtar Inc.

Parameters

- The temperature was constant at 35°C.
- The organic loading rate was constant at 6.2 g COD/g VSS/d, the feed composition is given on Table 1.
- The upflow velocity was constant at 0.5 m/h.

Scanning Electron Microscopy (SEM)

Granules were fixed in 3% gluteraldehyde solution for one hour, then dehydrated in a graded ethanol series, before critical point drying. These samples were mounted on an aluminum stub using copper tape and coated with carbon. Scanning electron microscopy was performed using an International Scientific Instruments DS-130 SEM.

COMPONENT	CONCENTRATION (mg/l)
Acetic Acid	2 000
Propionic Acid	500
Butyric Acid	500
NaOH	for pH adjustment
K_2HPO_4	200
$(NH_4)_2SO_4$	20
NH_4HCO_3	650
$NaHCO_3$	2 250
Yeast Extract	100
$CaCl_2 \cdot 2H_2O$ (to yield 100mg Ca^{2+}/l)	367.5
* TMS (Trace Metal Solution)	2 mL/L
*** TMS**	
$FeCl_2 \cdot 4H_2O$	2 000
H_3BO_3	50
$ZnCl_2$	50
$CuCl_2 \cdot 2H_2O$	40
$MnCl_2 \cdot 4H_2O$	500
$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	50
$AlCl_3$	30
$CoCl_2 \cdot 6H_2O$	150
$NiCl_2 \cdot 6H_2O$	500
Concentrated HCl	1 mL
Distilled Water	to make 1 litre

Table 1 Composition of Synthetic Feed

Energy Dispersive X-Ray Analysis (EDAX)

Samples were examined for elemental composition during SEM analysis using X-Ray Microanalysis System's, aPGT System III.

Light Microscopy

Unfixed samples were viewed on glass slides with slip covers after physical disruption, using a Zeiss Photomicroscope III.

RESULTS

The granules which were received from Paques-Lavalin were originally of a uniform dark (almost black) colour. After about 60 days of operation in our reactor, a number of granules began to appear which had a greyish colour, or were yellow-white. These grey and white granules had approximately the same size distribution as the original granules. There was no change in reactor performance (in terms of gas production, or COD reduction) upon the appearance of these granules [9].

Generally, black granules were more firm than grey ones, which were more firm than white. Black

and grey granules had regular, approximately round shapes. White granules were toroidal, and tended to break into irregular fragments.

SEM micrographs of the different granule types are presented as Figures 2, 3 & 4. The black granules had smooth surfaces, and were spherical or slightly ovoidal. The bacterial cells present were either filamentous or short curved rods. The surface of the grey granules was more irregular, having a more coarse texture. White granules were the most irregular, their surfaces had fissures and these granules were often broken.

Figure 2 Scanning Electron Micrograph of the Surface a Black Granule (46x)

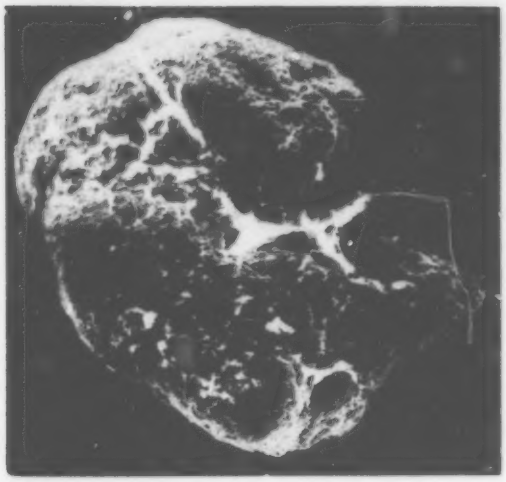

Figure 4. Scanning Electron Micrograph of the Surface of a White Granule (x 37.8)

Upon cutting the granules hemispherically, cross-sectional views of the granules were obtained for study (Figures 5, 6 & 7). The black granules were uniformly black throughout. The grey granules were stratified, having light coloured surfaces with concentric dark and light zones. The white granules were uniformly light coloured throughout, and usually had hollow cores into which the granule had collapsed creating their toroidal shape.

Figure 3. Scanning Electron Micrograph of the Surface of a Grey Granule (x 28.9)

Figure 5. Scanning Electron Micrograph of a Cross-Sectioned Black Granule (x 47)

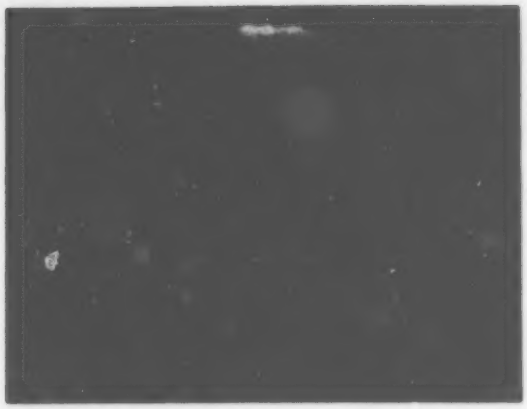

Figure 6. Scanning Electron Micrograph of a Cross-Sectioned Grey Granule (x 28.7)

Figure 7. Scanning Electron Micrograph of a Cross-Sectioned White Granule (x 46)

During study of the granules with SEM, elemental analysis was performed by EDAX. This analysis was performed on four regions of the granules referred to as: surface, periphery, half-radius, and core zones. The results of this analysis, in terms of relative abundance of each inorganic element are presented as Tables 2, 3 & 4. The black granules contained large concentrations of silicon and aluminum throughout. The grey contained similar concentrations of these elements in their core, but much lower concentrations toward their surface. White granules contained uniformly low levels of these two elements. Calcium concentrations were generally independent of the granule colour, perhaps due to the high (100 mg Ca^{++}/litre) in the waste water treated. The average ratio of sulphur/iron present within the granules was: black 2.6, grey 4, and white 7.2. This indicates that sulphur was more often associated with iron in the black granules, possibly as black ferrous sulfide. The elements sodium, potassium and chlorine were found to comprise a greater percentage of the inorganic material in the white granules than in the black or grey.

ELEMENT	SURFACE	PERIPHERY	½ R	CORE
Calcium	19.76	13.26	19.44	1.83
Iron	7.95	5.59	7.40	5.75
Copper	1.75	3.16	2.67	2.81
Sulphur	14.13	19.06	18.53	15.47
Phosphorous	19.66	21.45	15.47	15.62
Silicon	14.22	13.63	14.08	16.48
Aluminum	19.62	18.42	19.94	20.61
Potassium	0.58	1.18	0.58	0.73
Sodium	1.57	3.70	1.07	0.48
Chlorine	0.76	0.55	0.70	0.22

Table 2. EDAX Analysis (atom%) for a Cross-Sectioned Black Granule

ELEMENT	SURFACE	PERIPHERY	½ R	CORE
Calcium	18.72	15.31	17.49	18.24
Iron	6.26	8.04	7.62	5.69
Copper	4.31	9.06	3.58	3.78
Sulphur	34.87	28.62	18.87	17.74
Phosphorous	27.22	19.51	15.90	16.60
Silicon	2.39	3.84	13.91	15.35
Aluminum	1.55	3.80	18.58	19.05
Potassium	3.56	4.90	2.16	2.56
Sodium	0.11	4.70	1.30	0.66
Chlorine	1.01	2.22	0.60	0.32

Table 3. EDAX Analysis (atom%) from a Cross-Sectioned Grey Granule

ELEMENT	SURFACE	PERIPHERY	½ R	CORE
Calcium	12.18	18.39	14.98	n/a
Iron	3.86	4.60	4.49	n/a
Copper	6.17	7.97	8.64	n/a
Sulphur	31.17	26.18	35.17	n/a
Phosphorous	23.87	23.93	23.39	n/a
Silicon	1.89	3.81	1.43	n/a
Aluminum	1.05	1.07	0.00	n/a
Potassium	10.94	6.53	6.36	n/a
Sodium	7.30	5.12	2.85	n/a
Chlorine	1.58	2.42	2.67	n/a

Table 4. EDAX Analysis (atom%) from a Cross-Sectioned White Granule

Preliminary work with light microscopy, using magnifications below 2000x have failed to show different species between the granule types. Future work employing transmission electron microscopy will be performed to more fully evaluate the species present within the granules.

CONCLUSIONS

1. The granules used in our UASB reactors changed their colour from their original black colour, to grey and white, when operated at low upflow velocity, low organic loading rate and high calcium concentration.

2. The colour change appears to be related to differences in the inorganic element profiles of the granules.

ACKNOWLEDGEMENT

This work was supported by Paques-Lavalin and the Biotechnology Research Institute of Canada in Montreal. The authors express their gratitude for this support.

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P3-43
CRYSTALLINE POLY(β-HYDROXYALKANOATES): NATURE'S ADAPTABLE HELIX

CRYSTALLINE POLY (β-HYDROXYALKANOATES): AN ADAPTABLE HELIX

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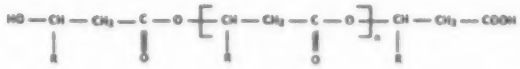
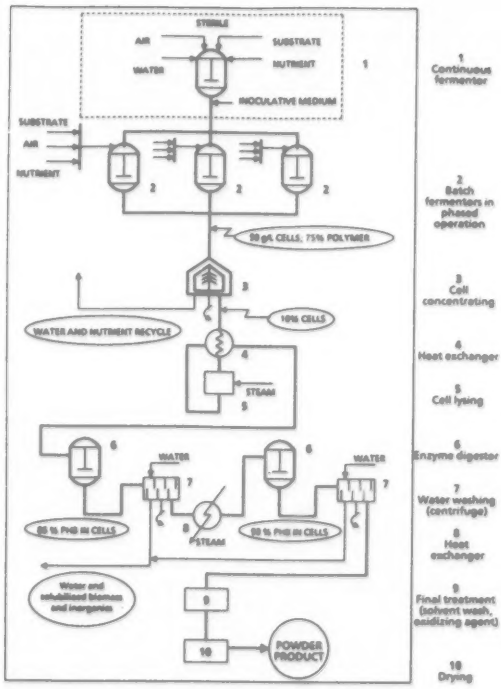
The family of bacterial copolyesters: poly-β-hydroxyalkanoates (PHA), with average sidechain lengths between C_1 and C_7 crystallize as a 2_1 helix in an orthorhombic lattice with two molecules per unit cell. The fiber repeat, or c dimension of the unit cell, varies continuously from 5.96 and 5.56Å for poly-β-hydroxybutyrate (PHB) and poly-β-hydroxyvalerate (PHV), respectively, to 4.53Å for PHA with average sidechain length between C_1 and C_7. This collapse of the c dimension while maintaining the 2_1 helical symmetry may be thought of as cyrstallization driven by sidechain packing influences. It is proposed that the PHA with long hydrocarbon sidechains form ordered sheets with the extended alkane branches in polyethylene-like domains. The melting points, glass transitions and fiber repeat change regularly as a function of average number of sidechain carbons for the whole family of PHA. X-ray diffraction of a melt crystallized PHA with C_5 sidechain indicates a maximum crystallinity of 25%, achieved only after several hours at room temperature. ^{13}C NMR spectra and relaxation times of the bulk phase amorphous regions of these polymers demonstrate the high degree of motional freedom of the sidechains and the significantly slower motion for the backbone carbons. ^{13}C NMR was also used to estimate the percent crystallinity which is in agreement with the X-ray diffraction results. Thus PHA represent a family of biodegradable plastics with properties ranging from thermoplastics for short sidechains to thermal elastomers for longer sidechains.

Les poly-β-hydroxyalkanoates (PHA) représentent une famille de copolyesters d'origine bactérienne. On les trouve sous forme de particules intracellulaires servant de substance de réserve. Pour une chaîne latérale variant de C_1 à C_7, les PHA cristallisent avec un axe hélicoidal 2_1, la valeur du pas de l'hélice allant de 5.96Å et 4.53Å. La chaîne latérale produit donc un refoulemnet qui est fonction de sa longueur (C_n). Le point de fusion et la température de transition vitreuse diminuent aussi systématiquement lorsque C_n augemnt. Par diffracion des rayons-x on peut montrer que pour une chaîne latérale de C_5, le PHA a un taux de cristallinité de 25%, ce qui est beaucoup moins que le PHB. La RMN ^{13}C du polymère brut et les rayons-x démontrent également que le taux de cristallinité est d'environ 25%. Cette famille de polyesters naturels offre un nouveau matériau industriel biodégradable qui, en fonction de sa composition va du thermoplastique à élastomère.

MOLECULAR STRUCTURE



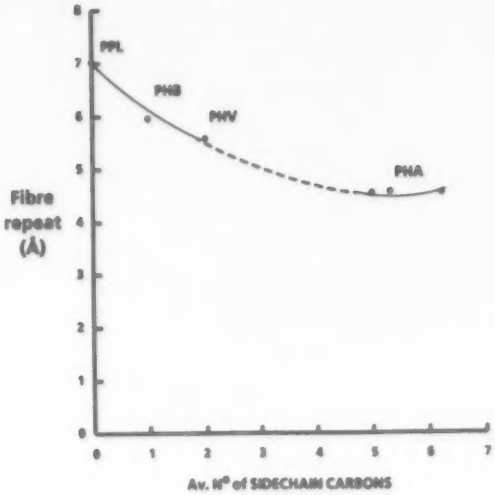
In the case of PHB R = CH_3 i.e. C_1 sidechain



Schematic of ICI native granule production/isolation process for BIOPOL™ material.

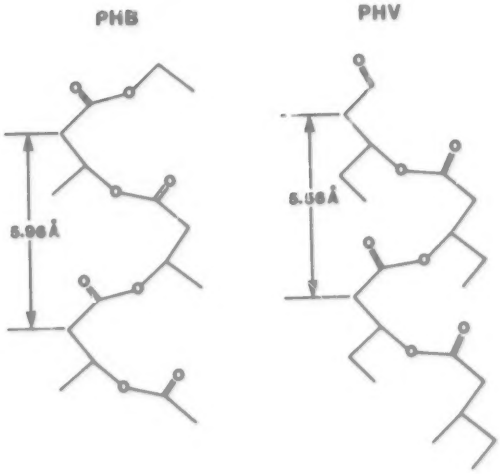
SEM micrograph of sectioned *Alcaligenes eutrophus* cells obtained from a growing culture, displaying the granules of PHB.

FIBER REPEAT of 2_1 HELIX PHA

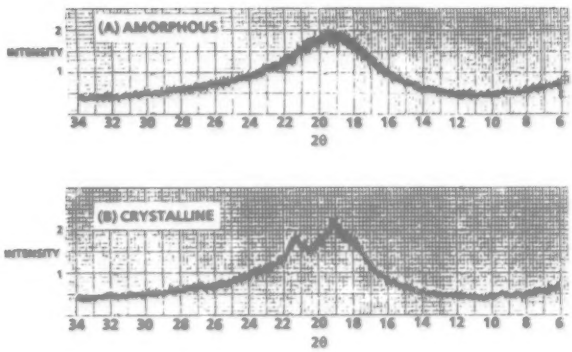


CONFORMATION of LONG SIDECHAIN of PHA

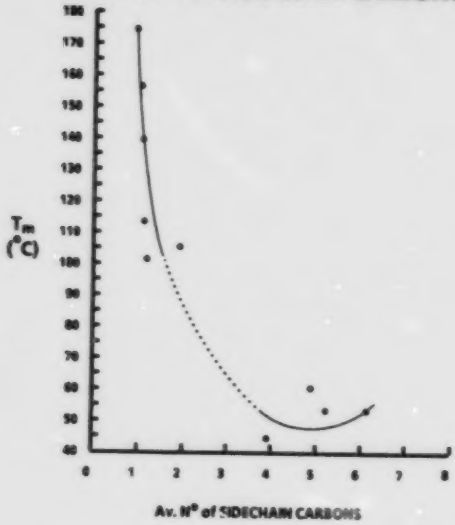
CRYSTALLINE CONFORMATION of PHB and PHV



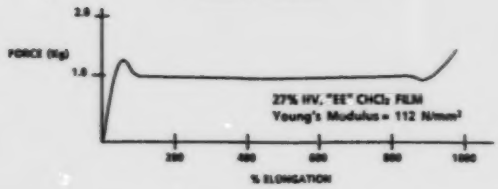
X-RAY DIFFRACTION OF PHA(C_6)

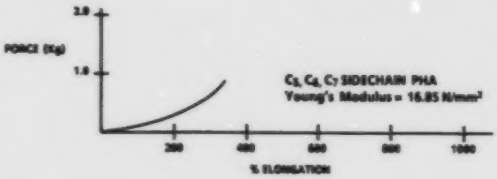


MELTING POINT (T_m) of PHA vs Av. N° of SIDECHAIN CARBONS

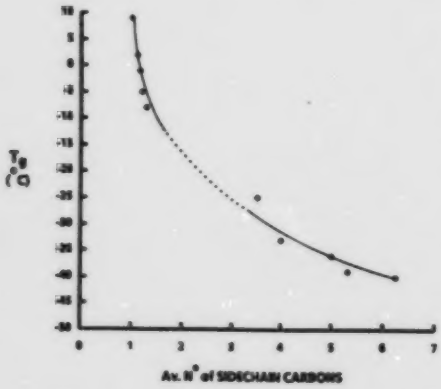


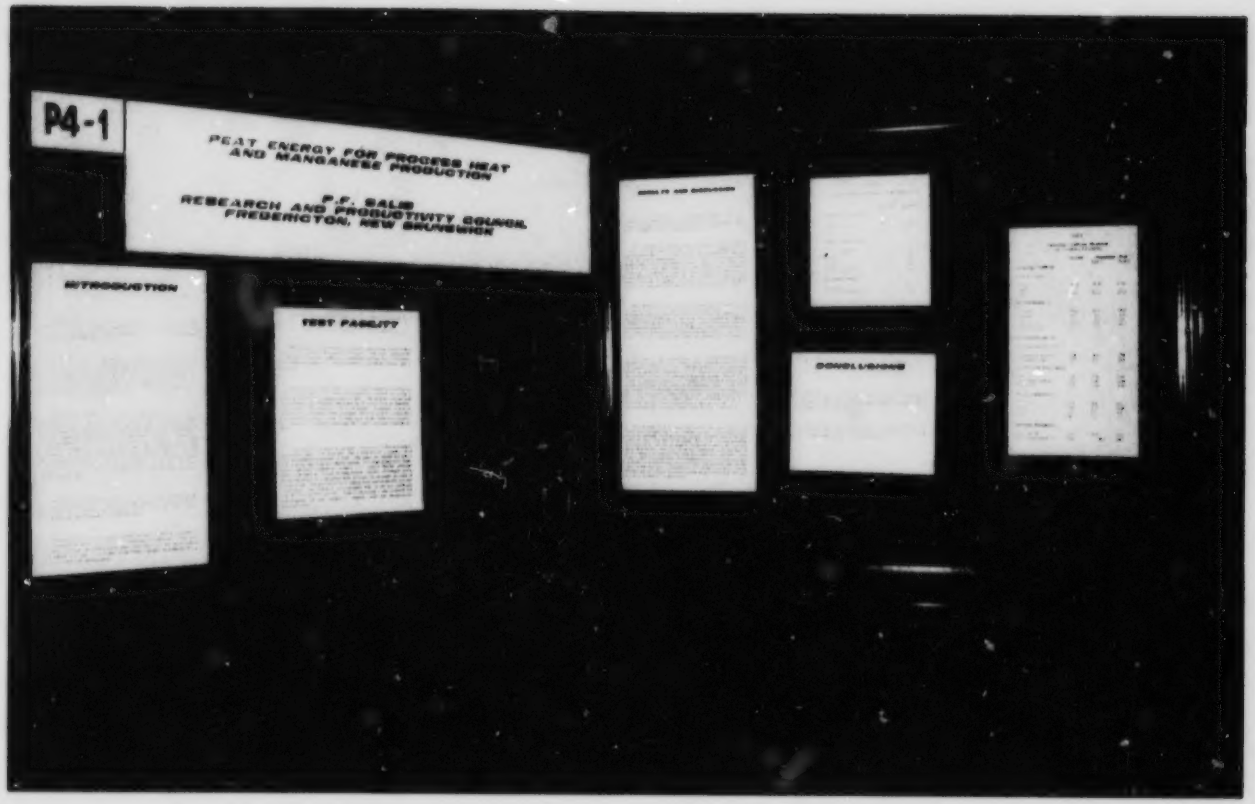
STRESS - STRAIN CURVES OF P(HB - co -HV) AND C_5, C_6, C_7 SIDECHAIN PHA
(RATE = 10 mm/min)





GLASS TRANSITION TEMPERATURE (T_g) of PHA as a FUNCTION of Av. SIDECHAIN LENGTH




P4-1
PEAT ENERGY FOR PROCESS HEAT
AND MANGANESE PRODUCTION
P.F. SALIB
RESEARCH AND PRODUCTIVITY COUNCIL
FREDERICTON, NEW BRUNSWICK
INTRODUCTION
TEST FACILITY
CONCLUSIONS

PEAT ENERGY FOR PROCESS HEAT AND MANGANESE PRODUCTION

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Trials on the burning of New Brunswick thermal and manganese peat were performed in a pilot scale circulating fluidized bed combustor (CFBC).

For thermal peat the combustion efficiency as measured by carbon burn-up was excellent at 97.8% at an excess air level of 13.5% and a bed temperature of 859°C. Carbon monoxide emission at 3000 ppm which is higher than typical values obtained when burning bitumenous coals. The moisture content of the peat tested was 40%. This did not appear to cause any operational problem with the exception of a temperature gradiant of 70°C between the top of the combustor and the feed point.

The manganese peat tested contained 40.5% ash, compared to 1.27% for the thermal peat. The manganese content of the ash was 16.5%. The manganese peat was successfully burnt in the CFBC unit and a high carbon conversion was possible. This was achieved despite the fact that the combustor was operated under reducing (substoichiometric) conditions to form monovalent manganese oxide in order to facilitate manganese extraction from the product ash. High carbon conversions of 93.7% and 94.7% were achieved at substoichiometric conditions corresponding to excess air levels of -15.6% and -35.6%. The manganese content of the product ash was approximately three times higher than those in the feed indicating that burning appears to be an effective method for concentrating the manganese in the solids for future extraction.

On a effectué des essais de combustion de tourbe thermique et de tourbe au manganèse provenant du Nouveau-Brunswick, dans un appareil de combustion à lit fluidisé à circulation.

Dans le cas de la tourbe thermique, l'efficacité de combustion, mesurée par la quantité de carbone brûlé, était élevée (97.8 %), en présence d'un excès d'air de 13.5 % et à une température de lit de 859°C. Toutefois, les émissions de monoxyde de carbone étaient élevées (3000 ppm), ce qui est considérablement plus élevé que les valeurs caractéristiques obtenues durant la combustion de charbon bitumineux. La teneur en humidité de la tourbe évaluée était élevée (40 %), mais cette teneur ne semblait causer aucun probléme opérationnel, à l'exception d'un gradient de température de 70°C entre la partie supérieure de l'appareil de combustion et le point d'introduction de la tourbe.

La tourbe au manganèse qui a été évaluée renfermait 40.5 % de cendres, en comparaison de 1.27% pour la tourbe thermique. L'appareil à lit fluidisé à circulation permettait de brûler efficacement la tourbe au manganèse, et it était possible d'obtenir un taux élevé de conversion du carbone. Ce taux élevé a été atteint malgré les conditions réductrices de combustion (conditions sous-stoechiométriques) qu'on avait choisies afin de faciliter l'extraction du manganèse contenu dans les cendres en y maintenant le Mn sous forme d'oxyde monovalent.

On a obtenu des taux élevés de conversion du carbone, soit 93.7 % et 94.7 %, à des rapports sous-stoechiométriques air/combustible de -15.6 % et -35.6 %. La teneur en manganèse dans les cendres était environ trois fois supérieure à la teneur dans la charge d'alimentation; ainsi, la combustion semble être une méthode efficace de concentration du manganèse dans les solides que l'on pourrait appliquer éventuellement au cours d'opérations d'extraction.

INTRODUCTION

New Brunswick has extensive peat resources (103 million tonnes occupying an area of about 60,000 hectares) which at present are primarily utilized for horticultural purposes. Two types of unutilized peat are thermal and manganese.

The thermal peat is similar in composition to horticultural peat but has a higher degree of humification (decomposition) which makes it unsuitable for soil conditioning. This material has a heating value of approximately 4000 to 5000 Btu/lb (50% moisture content) and an extremely low ash (1%) and sulphur content, which make it an ideal fuel. It is estimated that the thermal peat resources in New Brunswick are approximately 21 million tonnes (1).

The manganese peat is very different in composition to thermal and horticultural peat, it has a much greater ash content with a high concentration of manganese. The calorific value of the manganese peat is lower than thermal peat. The sample used in this study had a calorific value of 2826 Btu/lb (22% moisture content). Therefore, using manganese peat as a fuel source is less attractive but if the manganese metal is extracted from the ash resulting from the combustion of the peat, the situation could change. Manganese is a metal used principally in iron and steel manufacturing and since there is no domestic supply, Canadian production would be attractive. Annual comsumption of ore and 4000 tonnes battery and chemical grade manganese.

The primary objective of this study was to conduct combustion trials on the thermal and manganese peats in the circulating fluidized bed combustor (CFBC) at the Research and Productivity Council and to evaluate the performance of both as fuels.

The thermal peat was burned under normal oxidizing conditions. The manganese peat was tested in reducing conditions. This was necessary so that the manganese was converted into the monovalent form which is required in order to facilitate further treatment of the ash to recover the manganese.

TEST FACILITY

The Research and Productivity Council's circulating fluidized bed combustor is shown schematically in Figure 1. The main components of the system are the combustor, a primary cyclone and a standpipe for solid recirculation, a cooling section, a secondary cyclone and a baghouse.

The refractory lined combustor is 127 mm in diameter and has an overall height of 5.8 m. Solid recirculation is carried out using a primary cyclone, a standpipe and a J-valve. The primary cyclone and the standpipe are refractory lined and are 0.3 and 0.23 m in diameter, respectively. The latter is 2.74 m in height. A cooling section is attached to the bottom of the standpipe which is used to control bed temperture as well as giving an indication of the solid recirculation rate which is controlled by adjusting the J-valve's aeration and lift air flows.

The flue gases leaving the primary cyclone are cooled in a water-jacketed 6" pipe, 5.2 m in height. This is followed by a stainless steel 0.25 m diameter secondary cyclone. The gases are finally fed into a self cleaning dust collector which consists of 16 high temperture bags. Other auxiliary equipment includes a 0.5 million Btu/hr propane burner for start up. A solid feeding system, consists of a simple screw feeder mounted on a weighing scale provides an accurate account of the feed rate. The feed material is transported pneumatically into the combustor. The system is also equipped with on-line gas analyzers for CO, CO_2, O_2, NO_x and SO_2. A micro processor is also available for data-logging of gas analyzers outputs and for temperature measurements.

RESULTS AND DISCUSSION

The chemical analysis of thermal and manganese peat bulk samples are shown in Table 1. Feed preparation consisted of screening of over sized material (>1/8") and oven drying of the manganese peat from a moisture content of approximately 80% to 22%.

The combustor was started up using a propane burner to preheat a bed of sand (approximately 200 kg) to a temperature of approximately 600°C. Coal was fed into the combustor in order to bring the system temperature to 850°C. The coal feed was then stopped and peat feed was initiated from a separate feeder. Peat and air feed rates were then adjusted to the desired set of operating conditions. To maintain steady state operation with the thermal peat it was necessary to feed sand into the combustor to replace bed material lost due to attrition. Bed loss was not encountered when burning the manganese peat with its high ash content (40 % ash).

The thermal peat was burnt in an oxidizing atmosphere at an excess air level of 13.5% with a flue gas oxygen level of 2.5%. The manganese peat was burned at two levels of reducing conditions for the purpose of producing an ash from which manganese could be extracted. For the first test the manganese peat feed rate was adjusted to obtain approximately 1 % O_2 in the flue gas, while in the second test the feed rate was increased for further reduction of O_2 level in the flue gases. The test conditions, and results are summarized in Table 2.

Mass and energy balances were carried out for all three tests. Overall and component mass balances were accurate within 5% with the exception of the ash balance on the thermal peat. Ash which could not be accounted for amounted to 17.3%. This is to be expected since the thermal peat has a very low ash contact and a slight absolute error results in a large percentage error. Carbon

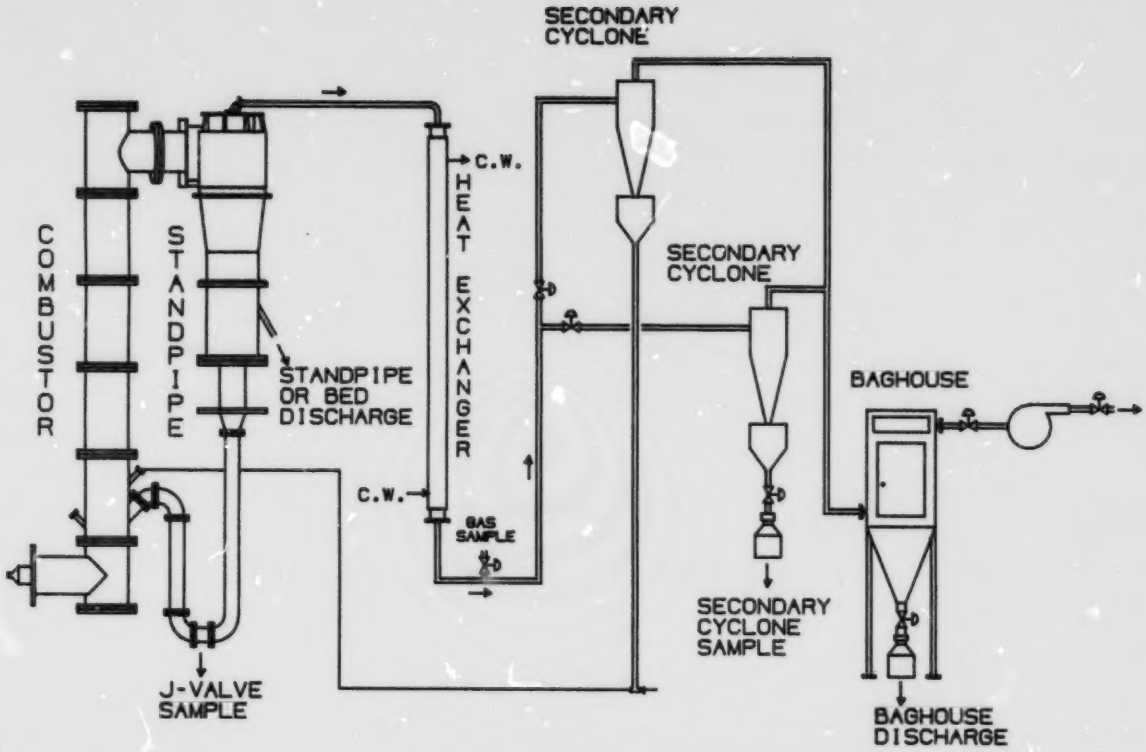

FIGURE 1: SCHEMATIC OF RPC CIRCULATING FLUIDIZED BED COMBUSTOR

conversion efficiency based on the percentage of the carbon in the discharge solids to that in the feed was 97.8% for thermal and approximately 94% for the manganese peat. The manganese content in the product ash was approximately 18% which is three times higher than its concentration in the feed. Therefore, burning the manganese peat appears to offer a way of concentrating the manganese in the solids for future extraction.

Energy balances were carried out and the results are summarized in Table 3. For the thermal peat, 10% of the heat was taken up by the cooling section, i.e., this much energy would be available for in-bed steam raising. Sensible heat in the flue gases accounted for 60% of the input. Part of this energy would be recovered in a convective section of a boiler or could be directed to a waste heat boiler. The losses from the combustor walls was high at 25.6% which is not unreasonably high for a pilot scale unit with a large surface area to volume ratio. For manganese peat no excess heat was available for in bed cooling (steam raising). The sensible and calorific value of the flue gases accounted for 64% of the total input and the balance was distributed between sensible heat in the solids and skin losses at 12 and 25%, respectively.

TABLE 1

Chemical Analyses of Thermal and Manganese Peat

	Thermal Peat	Manganese Peat
Proximate Analysis (wt %)		
Moisture	40.1	22.2
Ash	1.27	40.52
Volatiles	60.2	35.1
Ultimate Analysis (wt %)		
Carbon - Organic	30.30	20.46
- Inorganic		1.83
Hydrogen	3.33	1.83
Nitrogen	0.51	2.86
Sulphur	0.29	0.55
Oxygen (by difference)	24.2	10.8
Ash Analysis (wt %)		
Manganese	----	16.49
Calorific Value (Btu/lb)	5245	2826

TABLE 2

Operating Conditions, Measured and Calculated Parameters

	Thermal	Manganese Peat Test 1	Manganese Peat Test 2
Operating Conditions:			
Feedrates, kg/hr:			
Peat	26.80	39.40	51.84
Sand	2.32	-----	-----
Air	108.6	102.4	102.8
Air Distribution, %:			
Primary	56.4	63.9	58.8
Aeration	6.3	6.6	6.6
Lift	4.3	4.3	4.3
Peat Feeder	26.3	25.2	30.3
Sand Feeder	6.7	-----	-----
Measured Parameters:			
Bed Temperature, °C:3			
Combustor bottom	788	804	788
Combustor top	859	839	824
Ash Discharge Rates, Kg/hr:			
Bed	1.29	5.78	7.63
Secondary Cyclone	0.91	9.46	10.29
Baghouse	0.22	1.44	4.95
Flue gas composition:			
CO_2 %	17.1	18.9	19.1
O_2 %	2.5	1.37	0.23
CO %	0.3	0.5	4.2
NO_x	136	-----	-----
Calculated Parameters:			
Excess air, %	13.5	-15.6	-35.6
Carbon conversion, %	97.8	93.7	94.7

CONCLUSIONS

Both thermal and manganese peats were burned successfully in a pilot scale circulating fluidized bed combustor. High carbon conversion in the range of 94-97% was possible, however carbon monoxide emission was high.

The commercial use of thermal peat would be attractive in circumstances where supply was convenient to an end user, such as the case in the northeast coast of New Brunswick.

TABLE 3

Energy Balances

Run	Thermal Peat	Manganese Peat Test 1	Manganese Peat Test 2
INPUTS (KJ/hr) x 10^{-3}			
Peat	327.0	258.7	340.8
Air	-----	-----	-----
Total In	327.0	258.7	340.8
OUTPUTS (KJ/hr) x 10^{-3}			
Combustion Gas (dry)			
Sensible Heat	106.8	100.4	102.5
Calorific Value	3.16	5.04	44.4
Water	86.9	61.2	69.0
Baghouse Discharge	1.37	2.32	9.68
Cyclone Discharge	5.36	20.4	17.7
Bed Discharge	1.09	8.41	11.0
Heat Exchanger	31.72	-----	-----
Total Out	236.4	197.8	254.3
% Losses	27.7	23.6	25.4

ACKNOWLEDGEMENTS

The study was funded by the Renewable Energy Division, Energy Mines and Resources through the Bioenergy Development program. The author acknowledges the financial support and the help and co-operation of the project's Scientific Authority, Mr. J. Robert.

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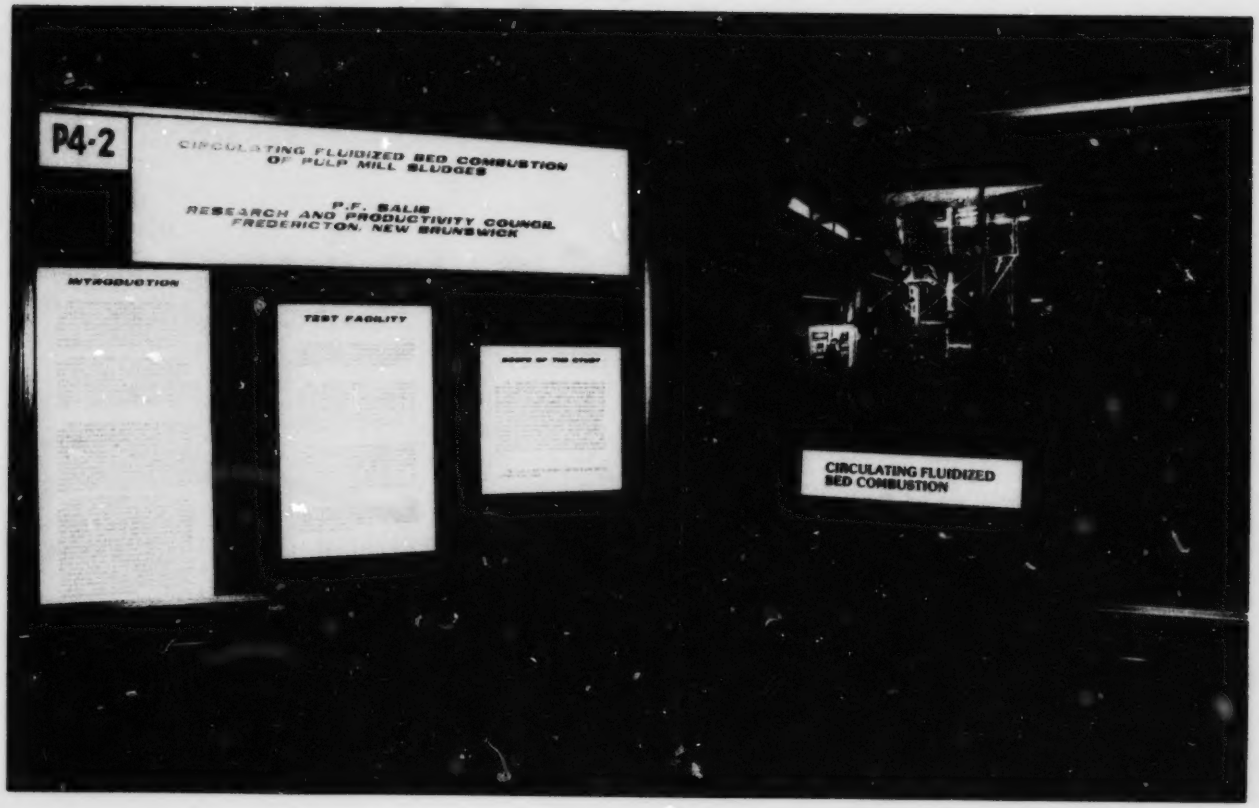
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CIRCULATING FLUIDIZED BED COMBUSTION
OF PULP MILL SLUDGES
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FREDERICTON, NEW BRUNSWICK
INTRODUCTION
TEST FACILITY
SCOPE OF THE STUDY
CIRCULATING FLUIDIZED
BED COMBUSTION

CIRCULATING FLUIDIZED BED COMBUSTION OF PULP MILL SLUDGES

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The combustion of pulp mill sludges in a pilot scale circulating fluidized bed Combustor (CFBC) will be investigated at the test facility of the New Brunswick Research and Productivity Council (RPC).

The project will be concerned with combustion tests on fresh and aged sludges from ground wood operations. The test burns will be carried out using a combination of coal, limestone, fresh and aged sludges.

The effect of sludge type, moisture content and supplementary fuel ratio on the combustion efficiency will be examined. Energy recovery options, potential operating problems such as slagging, and possible environmental impact will be evaluated.

On étudiera la combustion de boues rejetées par les usines de pâte dans l'appareil pilote de combustion à lit fluidisé à circulation des installations d'essais du Research and Productivity Council du Noveau-Brunswick.

Au cours du projet, on procédera à des essais de combustion avec des boues fraîches et des boues vieillies produites au cours de la fabrication de pâte méchanique de défibreur. On effectuera les essais de combustion en utilisant un mélange de charbon, de calcaire et de boues fraîches et vieillies. On étudiera l'effet du type de boue, de la teneur en humidité et du pouvoir calorifique supplémentaire sur l'efficacité de la combustion. On évaleura les options en matière de récupération d'énergie, les problèmes susceptibles de survenir au cours de la combustion, ainsi que les effets possibles sur l'environnement.

INTRODUCTION

The Canadian pulp and paper industry produces close to 2200 tonnes per day of dry sludge from waste water treatment operations. Almost all of this is produced in wood room clarifiers or primary clarifiers treating total mill effluents. Approximately 54 percent of the total is presently being incinerated, with most of the balance being landfilled. Long term environmental uncertainties associated with landfilling, as well as increasing costs and a drive to greater energy efficiency, makes it preferable to re-use the sludge (1).

Virtually all sludge incineration takes place in combination fuel/hog fuel boilers with the sludge representing a small percentage of the total feed. There are, however, some operational problems associated with burning sludges in conventional boilers. These include tube fouling, ash fusion and increased ash handling particularly when dealing with high ash sludges; aggravated slagging or clinker formation due to aluminum, titanium and/or solids from causticizing reagents; grate loading limitations; and, lack of ability to control excess air (2).

All of these technical problems can be eliminated or reduced considerably by using circulating fluidized bed technology. A circulating fluidized bed combustor (CFBC) has extremely good solid mixing and high rates of heat and mass transfer which makes it ideally suited for burning difficult, low heating value and high ash content fuels. The CFBC is a low temperature combustor (800-900°C) which would greatly reduce any ash fusion, slagging or clinker formation problems. A CFBC is also fuel versatile, thereby offering the possibility of burning a wide range of prime supplementary fuels/waste combinations. A circulating fluidized bed sludge incinerator would have many potential applications in New Brunswick and also across Canada.

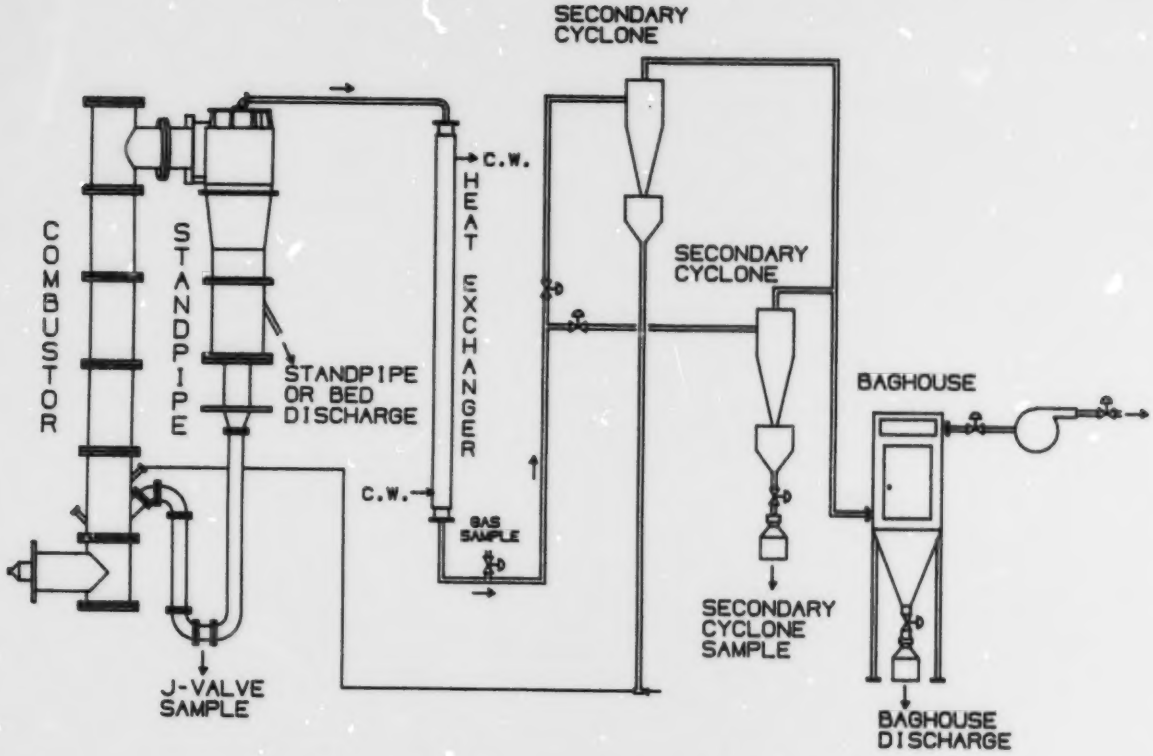

FIGURE: SCHEMATIC OF RPC CIRCULATING FLUIDIZED BED COMBUSTOR

A key to burning sludges either separately or in combination with other fuels, is the amount of preparation, particularly dewatering and drying, that is required prior to combustion. There are economic and performance trade offs between the amount of preparation and combustion efficiency, turndown capability, furnace size, steam capacity and feed rates of sludge and other fuels. Therefore, each case should be assessed on its own merits keeping in mind the end use of the generated energy and the overall energy requirements of a particular mill. Equally important are the characteristics of the product ashes. Potential increases in particulate emission, high concentration of trace heavy-metals in the fly ash, and leachants from ash disposal sites are among the questions which should be addressed in an environmental impact study. For this phase of development, a test program on a pilot scale circulating fluidized bed test unit will be important in order to determine the suitability of a particular sludge as a fuel and to obtain operating parameters for scale-up purposes.

TEST FACILITY

The Research and Productivity Council's Circulating Fluidized Bed Combustor is shown schematically in Figure 1. The main components of the system are the combustor, a primary cyclone and a standpipe for solid recirculation, a cooling section, a secondary cyclone and a baghouse.

The refractory lined combustor is 127 mm in diameter and has an overall height of 5.8 m. Solid recirculation is carried out using a primary cyclone, a standpipe and a J-valve. The primary cyclone and the standpipe are refractory lined and are 0.3 and 0.23 m in diameter, respectively. The latter is 2.74 m in height. A cooling section is attached to the bottom of the standpipe which is used to control bed temperature as well as giving an indication of the solid recirculation rate which is controlled by adjusting the J-valve's aereation and lift air flows.

The flue gases leaving the primary cyclone are cooled in a water-jacketed 6" pipe, 5.2 m in height. This is followed by a stainless steel 0.25 m diameter secondary cyclone. The gases are finally fed into a self cleaning dust collector which consists of 16 high temperature bags. Other auxiliary equipment includes a 0.5 million Btu/hr propane burner for start up. The system is also equipped with on-line gas analyzers for CO, CO_2, O_2, NO_x and SO_2. A micro processor is also available for data-logging of gas analyzers outputs and for temperature measurements.

A sludge feeding system is being developed for the material to be screw fed directly into the combustor. The system will consist of a live bottom bin, a metering screw, an airlock (star valve) and a conveying screw which will be either water or air cooled.

SCOPE OF THE STUDY

This study will be concerned with combustion tests on fresh and aged sludges from the ground wood operation of the Miramichi Pulp and Paper Co. Ltd. The test burns will be carried out using sludge in combination with Minto coal and limestone (for sulphur capture). The main objectives of the work are to examine the combustion characteristics of two sludges when burned separately and in combination with coal in different preparations; to monitor the combustion gases for CO, CO_2, O_2, SO_2, NO_x and unburnt hydrocarbons to ensure that environmental requirements have been met, to examine the ash products to determine any likely slagging or disposal problems; and to carry out mass and energy balances in order to determine energy recoveries and potential usage. A preliminary economic evaluation based on the specific sludges under consideration will also be carried out.

The work is still in progress and the results will be available in due course.

ACKNOWLEDGEMENTS

The study is funded by the Renewable Energy Division, Energy Mines and Resources through the Bioenergy Development program. The author acknowledges the financial support and the help and co-operation of the project's Scientific Authority, Mr. J. Robert.

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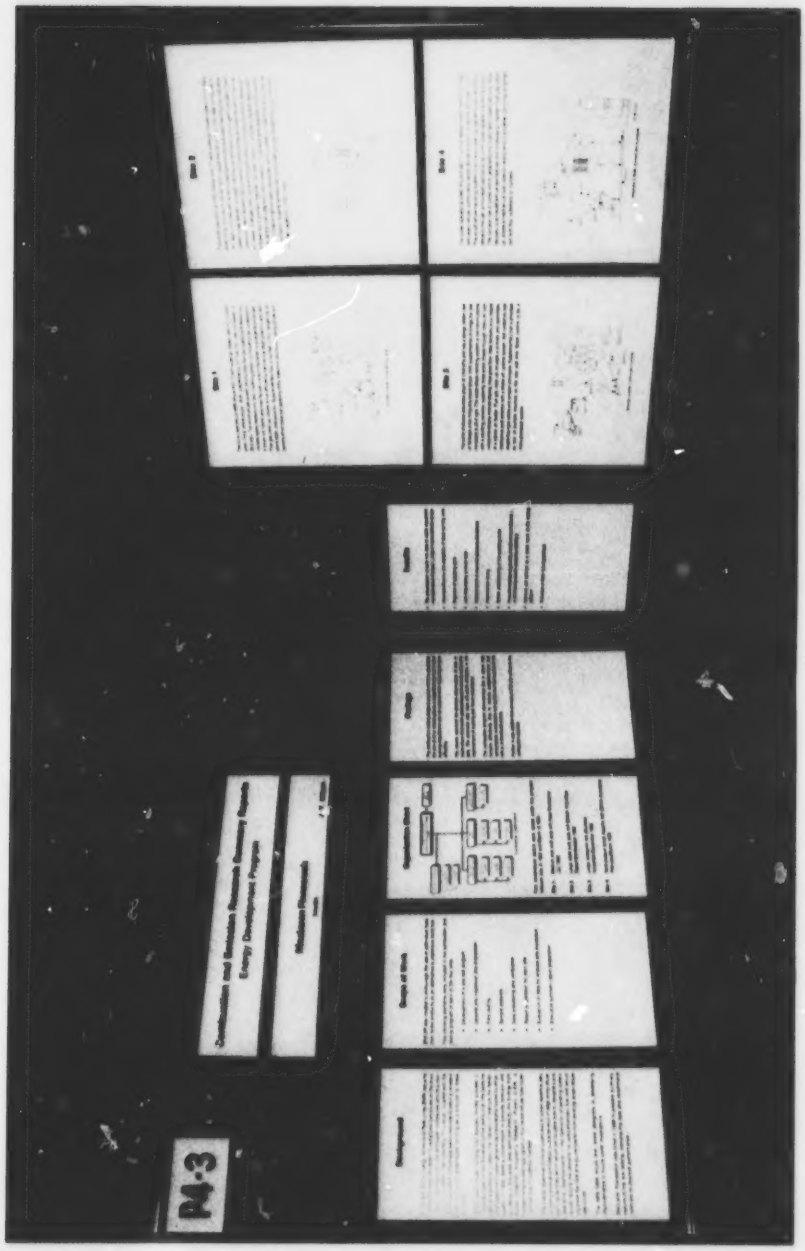
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COMBUSTION AND EMISSION RESEARCH SUMMARY REPORTS

J.-Y. Urbain and L. Sasaki

MacLaren Plansearch

As part of EMR's Wood-Refuse Boiler Program, field testing was completed on four combustion units operating in Canada. For each site, a report was produced which summarized operating parameters and presented relevant field measurements. These Summary Reports present the field test data in a more concise format - more meaningful and useful to boiler manufacturers, boiler operators, and environmental experts.

Nous avons effectué dans le cadre du Programme d'alimentation des chaudières avec des déchets de bois, des essais de combustion dans quatre installations au Canada. Pour chaque site, nous avons préparé un rapport qui résume les paramètres de fonctionnement et nous avons présenté les résultats de mesures d'émission gazeuse et de déchet solide. Ces brefs rapports présentent des résultats d'essais sous une forme plus concise et plus utile pour les fabricants de chaudières, pour les personnes chargées de les faire fonctionner et pour les experts environnementaux.

BACKGROUND

In the late 1970's Energy, Mines and Resources (EMR) became concerned about the effect of rising fossil fuel prices on the price of goods produced by pulp and paper companies and thus their ability to compete internationally. This issue, coupled with the growing problem of biomass waste disposal dictated a renewed effort to look to wood-waste burning as a solution to these problems.

While wood-refuse burning had enjoyed limited success in Canada, it was further hindered by the reality that little baseline data was available to assist the industry to improve the design and operation and steam generating installations fueled by wood-waste. In 1982, EMR's commitment to provide direction and guidance in this area, was demonstrated by the Energy from Forest (ENFOR) Program's Research Project C-235, a comprehensive testing program of four wood-refuse fired boiler installations throughout Canada.

The overall objective of the program was to obtain baseline data on combustion and emission characteristics of large wood-refuse burning facilities which would be valuable both to designers and operators in developing improvements to existing and future boiler installations. Improvements in the operation of existing boilers would reduce the demand for supplementary fuel and would increase the total energy recovered from existing wood-refuse resources.

As part of EMR's Bioenergy Development Program, MacLaren Plansearch was hired in 1988 to prepare summary reports of the site testing, interpret the data, and recommend methods to improve performance. These summary reports present the field test data in a more concise format - more meaningful and useful to boiler manufacturers, boiler operators, and environmental experts.

The following four wood-refuse boilers were tested between July 1982 and March 1985:

Site 1: a medium sized kraft pulp mill in New Brunswick - July 1982

Site 2: a large kraft pulp mill in British Columbia - September/October 1982

Site 3: a large newsprint mill in Quebec - November/December 1982

Site 4: a multi-product forest industry mill in British Columbia - February/March 1985

The following elements were included in the combustion and testing program of each of the four sites:

- development of a site test program
- detailed site inspection and preparation
- field testing
- sample analyses
- data processing and verification
- report preparation for each site
- evaluation of data for analysis and correlation
- executive summary report preparation

The ENFOR program was structured with three prime contractors responsible to the Scientific Authority, G.K. Lee of Energy, Mines and Resources Canada. The Canadian Boiler Society (CBS) was engaged to coordinate and monitor the project. The field work, processing of data, and preparation of the reports was carried out by Envirocon Eastern Limited (EEL) for Sites 1, 2 and 3, and SNC Inc. for Site 4.

As illustrated in the following organization chart, subcontractors to EEL include Battelle Columbus Laboratories, the Centre for Energy Studies - Technical University of Nova Scotia, and W.J. Howell Engineering Limited. SNC Inc. subcontractors included Arthur Gordon Environmental Evaluators Limited, B.C. Research, and Ontario Research Foundation.

Through the Canadian Boiler Society, Battelle Columbus Laboratories provided technical advice on the design of the project and auditing of EEL's quality control procedures for Sites 1, 2, and 3.

The American Boiler Manufacturers Associated and the United States Environmental Protection Agency (US EPA) provided assistance through a standing Technical Committee whose members included a representative from the American pulp and paper industry.

PROGRAM DESCRIPTION

Most of the wood-fired power boilers built during the past twenty years in North America were designed to burn wood waste as a means to reduce the waste, rather than to produce steam. Early wood-fired furnace designs incorporated many desirable characteristics to aid the combustion process. Unfortunately, in an effort to reduce costs, and due to the lack of information regarding furnace operation and boiler efficiency, designers and owners discarded many essential features such as computer process control, a good feed system, and good control of the overfire air distribution, to name a few. The result has been the construction of box-like furnaces which are relatively easy to maintain, but do not combust wood in the most efficient manner.

The objective of the ENFOR C-235 program was to create a data base of process and emission data for different wood burning units under diverse operating modes. This data base was to form the basis for improvements to existing units to burn more efficiently and to aid in the design of future units.

The following lists the monitored parameters and samples that were taken at each site (where applicable) and their subsequent analyses.

1. Wood-refuse :

   physical and chemical properties, moisture content, temperature.

2. Fuel oil :

   proximate and ultimate analyses, high heating value (HHV).

3. Combustion air :

   temperature, relative humidity, volumetric flow rates.

4. Furnace observations :

   grate conditions, flame brightness, degree of suspension burning, gas temperatures, grate temperatures.

5. Flue gas :

   gas stratification, particulate concentration, continuous analysis (CO_2, O_2, CO, SO_2, NO_x, total hydrocarbons), temperature, dust collector pressure drop.

6. Stack emissions :

   opacity, resistivity, continuous mass flow, particulate concentration, particle size distribution, gas analysis (O_2, CO_2, CO, NO_x, SO_2).

7. Source Assessment Sampling System (SASS).

8. Grate ash and hopper ash :

   proximate and ultimate analyses, HHV,fusion temperatures.

9. Boiler control room data.

Site 1

The first test series was conducted in July of 1982 at a medium-sized kraft mill located in New Brunswick. The mill produced bleached and unbleached kraft market pulp. The test boiler was converted to burn wood refuse and oil from its original service as a low-odour chemical recovery boiler.

The boiler operated at 4480 kPa at 400C with a design steam rate of 31.5 kg/s when firing wood-refuse. With supplemental oil fuel, the rate increased to 36.5 kg/s. The wood-refuse system recirculated the fuel supply and fed four variable speed feeders onto twin travelling grates. Combustion air was heated by a steam coil heater and heat recovery was accomplished by a large economizer. Flue gas clean up utilized a low efficiency mechanical dust collector and twin electrostatic precipitators. Supplementary fuel was burned in four tangential oil burners which had the capability of the maximum continuous rating of the unit.

Site 2

The second series of tests was conducted in September and October 1982 at a large kraft pulp mill located in British Columbia. Testing was conducted on the largest wood-refuse and oil-fired power boiler at the mill.

Since the test boiler was installed, it had been modified and retrofitted several times to increase boiler efficiency and availability and to reduce stack emissions. The selection of this boiler for testing was influenced by the boiler's relatively sophisticated computer control system. This boiler was one of the few in Canada with a multiple-level, optimising computer control system.

The boiler operated at 4300 kPa at 400C with a design steam rate of 31.5 kg/s when firing only wood-refuse. With supplemental oil fuel, the rate increased to 44.1 kg/s. It was fitted with a recirculating wood-refuse system feeding four variable speed screw feeders through mechanical stokers onto a gently sloped fixed grate floor. Heat recovery was by means of a horizontal economizer and a tubular air heater. Flue gas clean-up was accomplished by a Viscodyne inertial separator followed by a primary mechanical dust collector and two parallel secondary mechanical dust collectors. Ash collection was hydraulic and operated continuously. The relatively sophisticated computer control system maximized wood-refuse consumption. Supplementary fuel was provided by eight tangential oil burners with a full load capability of 56.7 kg/s.

Site 3

The third series of tests was conducted in November and December 1982 at a large newsprint mill located in northeastern Quebec. The mill processes included sodium-based sulphite pulping, stone groundwood manufacturing, thermomechanical pulping and newsprint production.

This unit was selected for testing because of its modern design. The furnace incorporated a steeply-included pinhole grate and a modern microprocessor-based control system was installed.

The boiler produced saturated steam at 1034 kPa and had a design steam rate of 18.9 kg/s when firing only wood-refuse. With supplemental oil firings the rate increased to 25.2 kg/s. The wood-refuse handling system was non-recirculating with a vibrating conveyor supplying three wood chutes through rotary air lock valves onto a steeply inclined sloping, fixed grate floor. Heat recovery was by means of a tubular air heater. Flue gas clean-up included a primary and secondary mechanical dust collector with a shave-off cyclone system. Ash collection was carried out by double flap-type valves and scraper conveyors. Supplementary fuel was provided by four oil burners mounted on the rear wall end. Boiler control was maintained by a micro-processor system.

Site 4

The fourth boiler test was conducted in February and March of 1985 on a wood-refuse and oil-fired boiler at a multi-product forest industry mill on Vancouver Island, British Columbia. The test boiler was the most recent boiler installed at the mill, which fed a main header in parallel with a number of smaller, older wood-firing units.

The boiler operated at 4480 kPa and 400C with a design steam rate of 50.4 kg/s with wood-refuse, combination wood-refuse and oil, or oil as the only fuel source. The wood-refuse handling system was of the circulating type and supplied eleven feeders through wind-swept spouts to fall onto three parallel travelling grates. The furnace had a bustle which separated the lower and upper furnace. Heat recovery was achieved with an economizer and a tubular air heater. Flue gas clean up utilized a mechanical dust collector and a venturi scrubber. Oil firing was carried out with four sidewall oil burners.

BENEFITS

A number of benefits were realized from the ENFOR program:

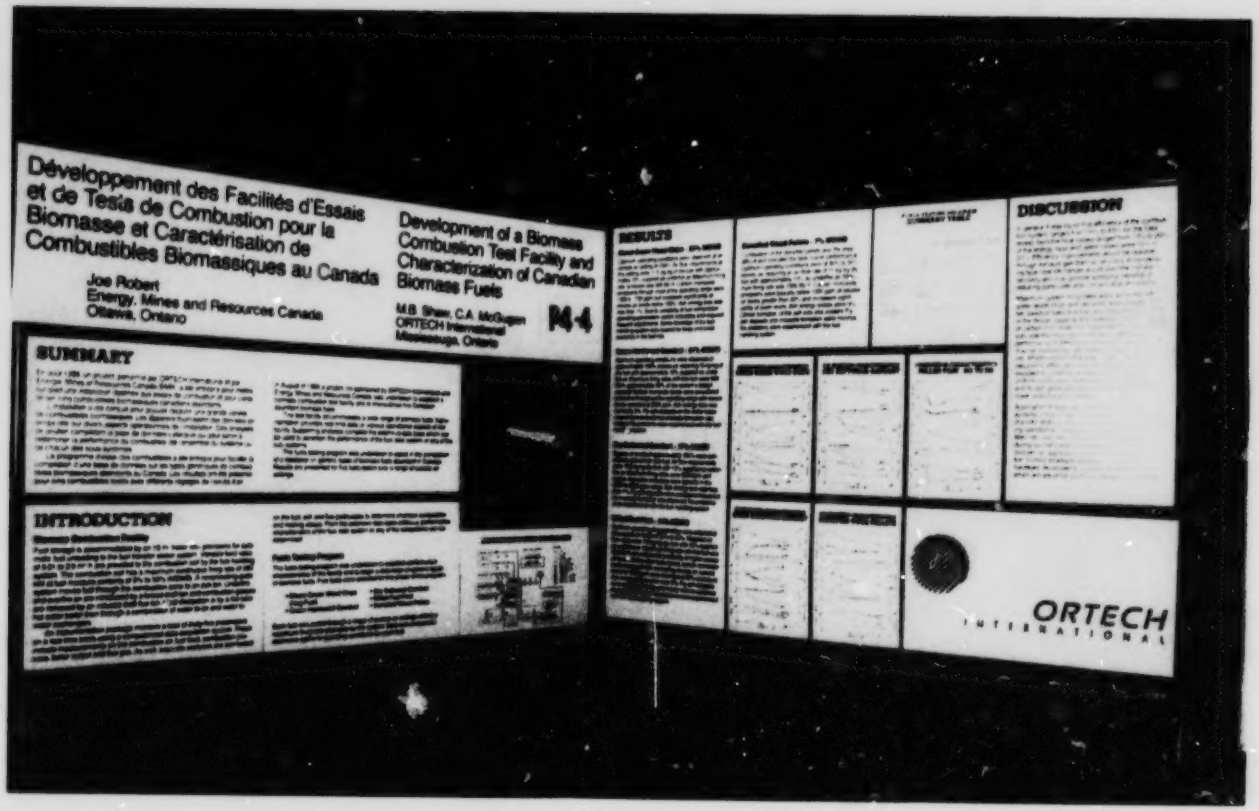
- the accumulation of base line data to assist equipment manufacturers in the development of improved boiler design
- improved efficiency and availability of wood burning units
- reduction of operating costs
- less dependency on fossil fuels
- implementation of improved operating procedures
- improved fuel mixing
- greater understanding of the operating limits of wood-refuse incinerators
- invaluable experience gained by the site crews and operators in maintaining certain operating conditions
- improved site facilities as a direct result of the testing program
- reduction of fossil fuel dependence

FINDINGS

The combustion testing program proved without a doubt that in wood burning installations the use of oil or natural gas as a supplementary fuel, can be reduced while improving furnace efficiency.

The reports represent the greatest accumulation of data on wood-refuse fired boiler operations and emissions collected to date. This extensive data base will assist designers in the improvement of existing and future installations.

The combustion program demonstrated that to obtain high furnace efficiency and to reduce supplementary fuel consumption, a consistent fuel quality must be supplied to the unit and monitored closely. Further, it was evident that process control can enhance the combustion process.


Développement des Facilités d'Essais et de Tests de Combustion pour la Biomasse et Caractérisation de Combustibles Biomassiques au Canada
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Development of a Biomass Combustion Test Facility and Characterization of Canadian Biomass Fuels
M.B. Shaw, C.A. McGugan
ORTECH International
Mississauga, Ontario
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SUMMARY
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INTERNATIONAL

DÉVELOPPEMENT ET MISE EN OEUVRE DES FACILITÉS D'ESSAIS ET DE TESTS DE COMBUSTION POUR LA BIOMASSE ET CARACTÉRISATION DE CINQ COMBUSTIBLES BIOMASSIQUES ABONDANTS AU CANADA
DEVELOPMENT AND COMMISSIONING OF A BIOMASS COMBUSTION TEST FACILITY AND CHARACTERIZATION OF FIVE ABUNDANT CANADIAN BIOMASS FUELS

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Mississauga, Ontario

En août 1986, un project, parrainné par ORTECH International et par Énergie, Mines et Ressources Canada (EMR), a été entrepris pour mettre sur pied une installation destinée aux essais de combustion et pour caractériser cinq combustibles biomassiques canadiens abondants.
L'installation a été conçue pour pouvoir recevoir une grande variété de combustibles biomassiques. Les appareils fournissent des données en temps réel sur divers aspects opérationnels de l'installation. Des analyses de soutien complètent la base de données extensive qui peut servir à déterminer la performance du combustible, de l'ensemble du système ou de chacun des sous-systèmes.
Le programme d'essai des combustibles a été entrepris pour faciliter la compilation d'une base de données sur les types génériques de combustibles biomassiques abondants au Canada. Les résultats ont été présenté pour cinq combustibles testés avec différents réglages de l'excès d'air.

In August of 1986 a project, co-sponsored by ORTECH International and Energy, Mines and Resources Canada, was undertaken to establish a biomass combustion test facility and to characterize five Canadian abundant biomass fuels.
The test facility accommodates a wide range of biomass fuels. Instrumentation provides real time data on various operational aspects of the facility. Supporting analyses complete the extensive data base which can be used to ascertain the performance of the fuel, total system or any of the sub-systems.
The fuels testing program was undertaken to assist in the compilation of a data base on generic types of biomass fuels abundant in Canada. Results are presented for five fuels tested over a range of excess air settings.

INTRODUCTION

Biomass Combustion Facility

Fuel storage is accommodated by an 18 m^3 trailer with provisions for automatic fuel unloading to the fuel transfer/stoker system. Variable feed rates of 0.01 to 2.0 m^3/h are provided to the combustion cell by the fuel handling system. The combustion cell has a maximum continuous firing rate of 300 kW at fuel moisture contents of 5% to 50% (MCWB). A reciprocating grate system moves fuel through the combustion zone to an ash bin. Underfire and overfire air are introduced by a forced draft fan and combustion gases are removed by an induced draft flue fan. Heat dissipation is by a fire tube hot water boiler then through a combination of water to air and water to water heat exchangers.

An instrumentation package monitors a total of thirty-five parameters on a real time basis using a computerized data acquisition system. These include measurements on the combustion air, fuel feed, combustion process, boiler output and flue gas. As well, separate analyses are conducted on the fuel, ash and flue particulates to determine chemical composition and heating values. From the extensive data base collected, performance characteristics of the fuel, total system or any of the subsystems can be determined.

Fuels Testing Program

The fuels testing program was undertaken to establish performance characteristics of the facility and to begin a data base on generic types of biomass fuels. Five fuels were selected for this phase of the program:

- Mixed Green Wood Chips (Hog Fuel)
- Green Hardwood Sawdust
- Dry Softwood Sawdust
- Milled Fuel Peat
- Densified Wood Pellets

Each fuel was tested through a range of excess air settings and at a maximum firing rate attainable by the system (Figures 1 to 5). Data was analyzed to determine optimum operating conditions for each fuel (Table 1).

RESULTS

Mixed Green Wood Chips - 35% MCWB

Optimum operating conditions were observed at an excess air setting of 100%. Airflow requirements at this setting were 11.5 kg/kg of dry fuel with approximately 10% supplied as underfire air. Maximum firing rate achieved was 920 MJ/h. Carbon monoxide emissions through most of the operating range were 1300 to 1700 ppm but increased significantly at excess levels below 100%. Ash energy loss was less than 1%. Due to variability of fuel composition operating parameters varied noticeably and required frequent adjustments. Some blockage of the fuel handling system was caused by twigs and small branches in the fuel mix.

Green Hardwood Sawdust - 51% MCWB

Optimum operating conditions were observed at approximately 140% excess air, requiring 15 kg/kg of dry fuel with approximately 10% supplied as underfire air. Maximum firing rates with this fuel were 520 MJ/h, approximately 50% of the system's design capacity. Carbon monoxide levels were considered excessive throughout the operating range with lowest levels recorded at 3150 ppm. Ash energy loss was nominally 2%. Fly ash deposits on the boiler tubes were at normal levels but creosote formation was evident. No problems were experienced with the fuel handling system.

Dry Softwood Sawdust - 17% MCWB

Excess air levels of approximately 100% were considered optimum for this fuel. Airflow requirements were 10.5 kg/kg dry fuel with 13% supplied as underfire air. Maximum firing rates were 580 MJ/h and carbon monoxide emissions were typically in the 4000 to 5000 ppm range. Ash energy loss was less than 1%. Fly ash deposits were considered heavy but no creosote formation was observed. No problems were experienced with the fuel handling system.

Milled Fuel Peat - 44% MCWB

Optimum operating characteristics were selected at low excess air levels of 30% to 35%. Required airflow rates were 7.8 kg/kg dry fuel with 18% supplied as underfire air. Maximum firing rate with this fuel was 580 MJ/h and reduced dramatically at higher excess air levels. Unlike other fuels tested, carbon monoxide levels increased with increasing excess air. Lowest levels of 1600 ppm were recorded at 30% excess air. Ash energy losses were near 2%. Fly ash deposits were considered to be very heavy with no evidence of creosote formation. No problems were experienced with the fuel handling system.

Densified Wood Pellets - 7% MCWB

Combustion of the densified pellets was the least difficult and indicated the best overall performance. Optimum operating conditions were at 40% to 50% excess air, requiring an airflow rate of 11 kg/kg dry fuel with approximately 10% as underfire air. Maximum firing rate was 1000 MJ/h. Carbon monoxide emissions were typically below 1000 ppm at excess air levels greater than 40% and increased significantly at lower levels. Ash energy losses were 5%. Clinker formation of the ash was also evident. Fly ash deposits and creosote formation were minimal. No problems were experienced with the fuel handling system.

DISCUSSION

In general it was found that efficiency of the combustion system ranged from 55% to 65% for the fuels tested. Sensible heat losses ranged from 13% to 20% of the energy input and latent losses were 10% to 25%. Efficiency improvements would be realized through exhaust gas thermal recovery. A condensing type heat exchanger would yield the highest recovery and may provide additional benefits of reducing particulate and condensable emissions.

Maximum system firing rates were achieved with green wood chips and densified wood pellets. The two sawdust fuels and fuel peat fired at 50% to 60% of the design capacity and released high emissions of carbon monoxide. It is suspected that fuel particle size was the most significant factor affecting the performance of these fuels although improvements may be realized by optimization of the combustion cell. Modifications to the grate system would be required to effectively increase the surface area exposed to underfire air thereby providing more uniform combustion. At the same time, channeling and fly ash generation would reduce as a result of lower underfire air velocities.

Application of automatic stoker fed combustion systems in the smaller size ranges may experience dramatic shifts in performance as a result of changing operational conditions, i.e. fuel composition, mass feed rate, load, etc. This was frequently observed during our fuels testing program and is cause for concern on applications requiring unattended operation. Control strategies should be investigated and hardware developed to provide integrated systems which will adjust for common operational variables.

Figure 1
Mixed Green Wood Chips

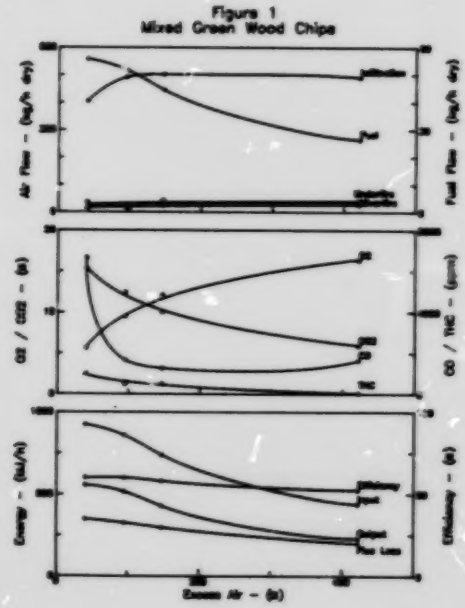


Figure 2
Green Hardwood Sawdust

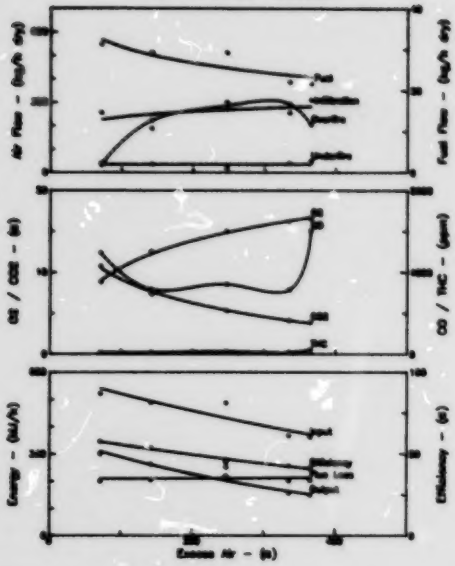


Figure 3
Dry Softwood Sawdust

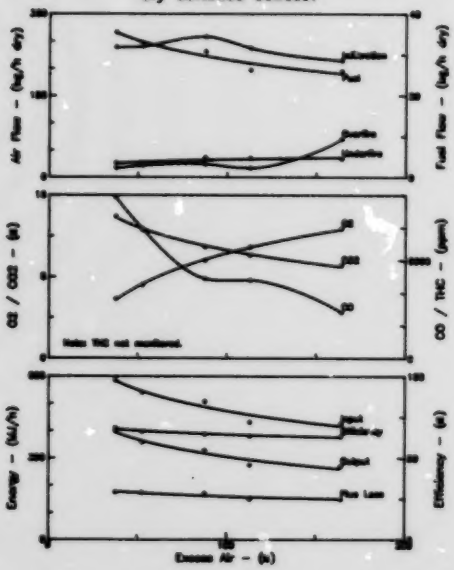


Figure 4
Milled Peat - H5 to H8

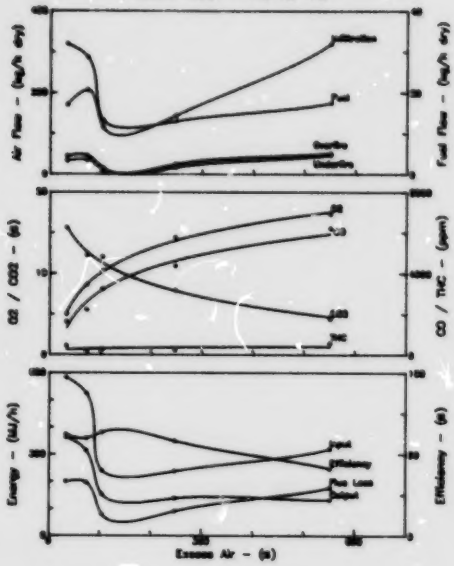


Figure 5
Densified Wood Pellets

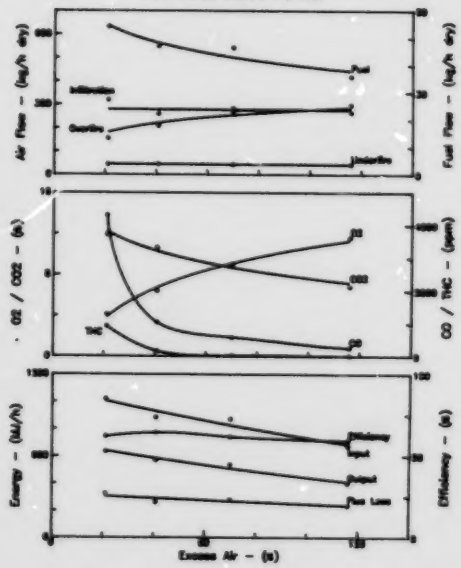
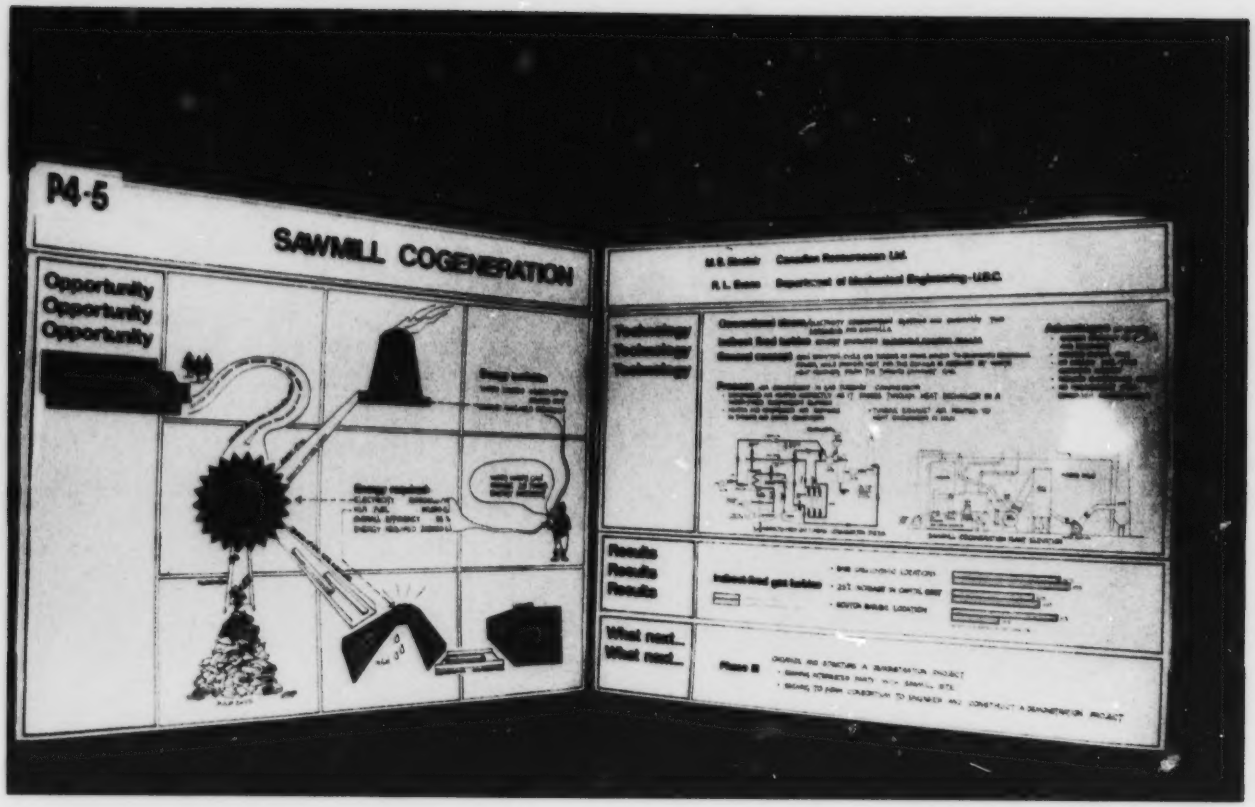


Table I
Results at Optimum Operating Conditions

		Wood Chips	Hardwood Sawdust	Softwood Sawdust	Milled Peat	Densified Pellets
Energy Data						
Input	MJ/h	857	488	507	583	882
Output	% of Input	60	54	65	62	64
Sensible Losses	% of Input	16	13	18	13	19
Latent Losses (incl. Hydrogen)	% of Input	20	26	12	20	9
Hydrogen & Reaction Losses	% of Input	2	3	3	1	1
Ash Losses	% of Input	<1.0	2	<1.0	2	5
Fuel / Air Data						
Fuel Mass Flow Rate	kg/h D.B.	52	29	31	32	47
Fuel Moisture Content	% W.B.	35	51	17	44	7
Excess Air Factor	%	95	142	88	33	41
Total Air Flow	kg/kg D.B.	10	15	10	8	11
Underfire Air	kg/kg D.B.	1	1	1	1	1
Emissions						
Carbon Monoxide	ppm	1660	3154	4865	1625	1030
Total Hydrocarbons	ppm	481	82	- - -	444	60
Smoke Number		4	6	7	7	9


P4-5
SAWMILL COGENERATION
Opportunity
Opportunity
Opportunity
[redacted]
Technology
Technology
Technology
Results
Results
Results
What next...
What next...

WOODWASTE-FUELLED, INDIRECTLY-FIRED GAS TURBINE COGENERATION PLANT FOR SAWMILL APPLICATIONS

M.S. Sinclair R.L. Evans

Canadian Resourcecon Ltd. R.L. Evans & Associates

ABSTRACT

The objective of this project is to develop a cost-effective system to generate electricity and dry kiln heat for sawmills, using an indirectly-fired gas turbine cycle. Sawmill residues are used as fuel to heat clean air which will power the turbine before exhausting through a heat exchanger in the lumber dry kiln. Based upon the generic design developed in Phase I of the project, a preliminary engineering design and financial analysis of a specific site was undertaken in Phase II.

Ce project vise à mettre au point un système rentable permettant de produire de l'électricité et de la chaleur pour les séchoirs à bois, dans les scieries, au moyen d'un cycle à turbine à gaz et à chauffe indirecte. Les résidus de la scierie sont utilises comme combustible pour chauffer de l'air propre qui alimentera la turbine avant d'être évacué par l'intermédiaire d'un échangeur de chaleur dans le séchoir à bois. Au cours de la phase II, on a entrepris une analyse technique et financière préliminaire, basée sur le plan général conçu lors de la phase I du projet, pour un site de démonstration spécifique.

INTRODUCTION

Although most sawmills generate more than enough woodwaste to be potentially self-sufficient in both dry-kiln heat and electricity requirements, it is not generally economically viable to use conventional Rankine cycle steam cogeneration systems at the sawmill scale of operation. The overall objective of this project, therefore, is to develop a cost-effective woodwaste-fired power generation and dry kiln heating system for sawmill applications.

The system proposed and evaluated in this project is a woodwaste-fuelled, indirectly-fired gas turbine cogeneration plant. Research, design and development of the system, funded by the Bioenergy Development Program of the Renewable Energy Branch of EMR Canada, has taken place in a number of phases. In Phase I of this project, completed in February 1987, a generic preliminary engineering design and financial evaluation were prepared for a cogeneration system of this type.

Phase II of the project, completed in March 1988, advanced the generic design of Phase I by preparing a preliminary engineering design and financial analysis of the system at a specific sawmill site. This paper summarizes the Phase II report prepared for EMR Canada and details the objectives of Phase III of the project, which is currently in progress.

SITE DESCRIPTION

After reviewing the Phase I report, British Columbia Forest Products (now Fletcher Challenge Canada) indicated that it was interested in having its sawmill at Boston Bar, B.C. considered as a potential demonstration site. This mill, located on the Fraser River about 190 kilometres by road northeast of Vancouver, cuts about 100 million board feet of lumber annually, of which 30 percent is currently kiln-dried using propane as a fuel. The company planned to increase the kiln-dried proportion of its output to at least 60 percent within a year, requiring the construction of another kiln.

With the planned expansion in kiln-dried output, the company would increase its propane consumption considerably if it were to continue using this fuel. Given the high cost of propane to the mill ($8/GJ versus $3.50 for B.C. mills with access to natural gas service), the company also planned to install a wood-fired burner to provide heat for the kilns. Its consideration as a potential demonstration site therefore appeared to be timely. Electricity to the mill is supplied from the B.C. Hydro grid at standard industrial rates ($0.0264/kWh plus $6.01/kW monthly demand charge).

COGENERATION SYSTEM DESIGN

A number of alternative system configurations were identified and preliminary engineering designs prepared for each. Equipment suppliers were contacted to establish the availability and cost of system components. The following three options were considered:

Option 1: woodwastes are combusted in a wet cell type hot gas generator. Hot gases leaving the combustor are directed into a tubular recuperative air heater before going into a 600 kW (net output) turbine. Turbine exhaust and flue gas are then directed through an oil heater which provides heat input of 7,000 kW for the dry kilns.

Option 2: provides the same electrical and heat output as Option 1, but uses a down-fired suspension burner unit, together with an integral air heater heat exchanger which has both convective and radiant sections. The fuel for the suspension burner consists of clean sawdust which is first dried to a moisture content of approximately 10 percent. A hot oil kiln heating system is also employed in Option 2. Figure 1 shows a flow chart for the Option 2 configuration.

Option 3: represents a commercial-scale configuration with an electrical output of 1,800 kW, which is near the mill's average requirement, and sufficient heat output for the three dry kilns. The layout of the system is similar to that of Option 2, except that the thermal oil kiln heating system is replaced with a system of air-to-air heat exchangers in the kilns.

After examining these three options, Options 2 and 3 were short-listed for consideration in the financial analysis and, ultimately, in a demonstration project. Option 1 is not a preferred option for two reasons: first, the capital cost estimate is significantly greater than for Option 2; second, a major technical risk exists with respect to the design, fabrication, and cost of the tubular recuperative air heater.

FINANCIAL ANALYSIS

Projected capital and operating costs of Options 2 and 3 were balanced against savings in purchased fuel and electricity costs in a computerized financial feasibility model. This model calculated the after-tax internal rate of return on the two systems and examined the sensitivity of the rates of return to changes in a number of variables, including: base year energy prices, rates of energy price escalation, capital cost, debt/equity ratio, and project lifetime. Rates of return are

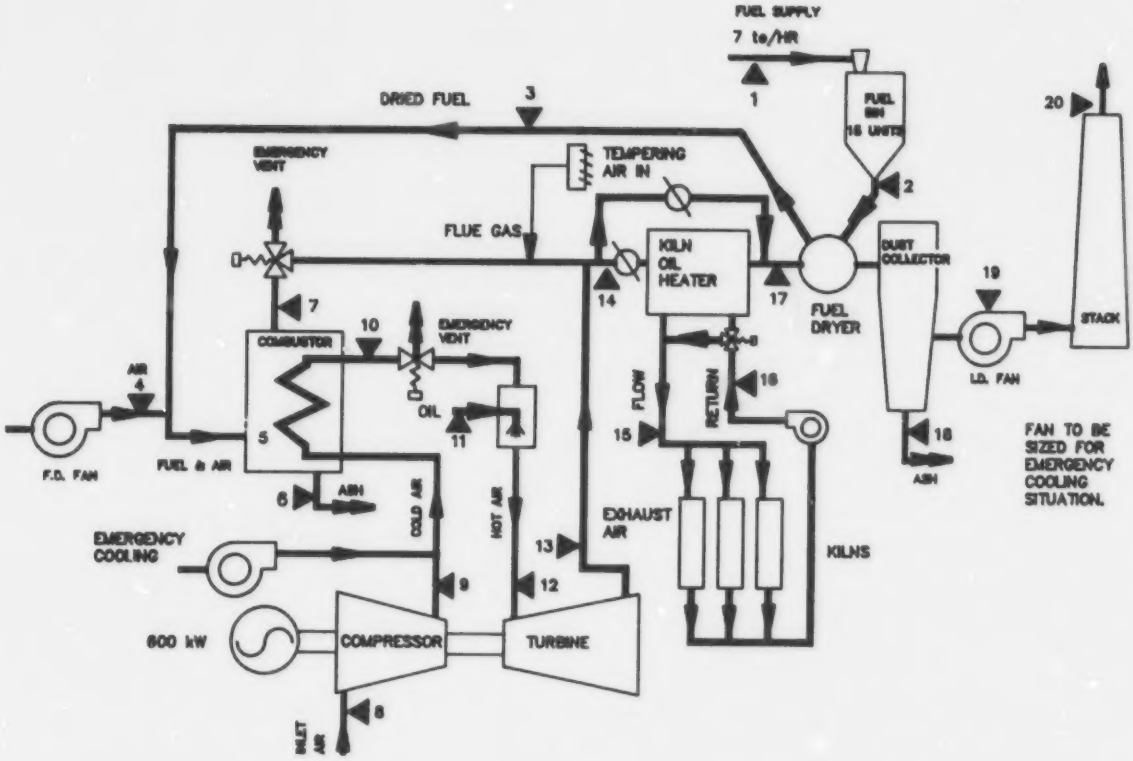


FIGURE 1: PRELIMINARY FLOW CHART FOR SAWMILL COGENERATION / SAWDUST FUEL

FLOW DATA								
PT.	ENERGY FLOW (o)		MASS FLOW		TEMPERATURE		PRESSURE	
	MBTU/HR	MW	LB/SEC	KG/SEC	°F	°C	LB/IN²	KPA
1			4.3	1.95	60	15.5	15	101
2			2.5	1.14	60	15.5	15	101
3			1.6	0.73	60	15.5	15	101
4			13.5	6.14	60	15.5	15	101
5	37.0	10.8	15.5	7.03	2450	1343	16	108
6			.016	.007	100			
7	24.5	7.2	15.5	7.03	1670	910	15	101
8			13.4	6.1	60	15.5	15	101
9	4.9	1.4	13.4	6.1	491	255	89	610
10	17.4	5.1	13.4	6.1	1400	760	85	585
11		START - UP ONLY						
12	17.4	5.1	13.4	6.1	1400	760	81	560
13	9.2	2.7	13.4	6.1	822	438	15	101
14	33.7	9.8	28.9	13.1	1241	672	15	101
15	107	31	110	50	450	232	25	168
16	83	24.3	110	50	350	177	25	168
17	9.7	2.8	28.9	13.1	448	231	13	88
18			0.16	.007	100	38	15	101
19			28.8	13.5	310	154	12	81
20			29.8	13.5	310	154	15	101

(o) NOTES:
Based on (enthalpy)h=0 @ 60 °F

calculated not only for the overall system, but also for the incremental cost of adding the electrical generation portion of the system to a wood-fired kiln drying system.

Option 2: The capital cost of Option 2 is estimated at $3.3 million, while annual operating costs are estimated at about $200,000. With current propane and electricity prices at the Boston Bar site, this system would reduce purchased energy costs by more then $800,000 annually with the planned increase in kiln-dried lumber output.

While the overall system generates an attractive rate of return (36.5 percent in the Base Case), the rate of return on the incremental investment required for electrical generation is very low without substantial capital grants (2.1 percent in the Base Case). The low return on the incremental electric generation can be attributed directly to the 600 kW demonstration scale of the system.

Option 3: This option is intended to illustrate the potential of the cogeneration system at a commercial scale and under more favourable electricity price circumstances than exist at the Boston Bar site. In this case it is assumed that the system will operate at a high load factor at the full output of 1,800 kW, with the electrical output valued at 5 cents per kWh. In the Base Case analysis of this option, natural gas priced at $4.50 per GJ is assumed as the kiln heating fuel. In effect, this case would be representative of a northern Ontario.location.

In the Base Case analysis of Option 3, the after-tax rates of return on the electric generating portion of the system (45 percent) and on the overall system (42 percent) are both very acceptable. A 25 percent increase in capital cost would reduce the after-tax IRR to 34 percent for the electric generation portion of the system, a level that is still acceptable.

CONCLUSIONS

In the context of the system design, preliminary engineering, and budget prices developed, we believe that the indirect-fired cogeneration approach is technically and economically sound. One of the key technical problems, a workable combustor/air heater arrangement, appears to be successfully addressed by the combined unit upon which Options 2 and 3 are based.

The reduced scale of operation associated with the demonstration-scale Option 2 system and low electricity rates in British Columbia combine to provide an inadequate rate of return at the Boston Bar site without substantial outside support for a demonstration project. Still, given the technical risks, the 600 kW scale may be appropriate for a first project utilizing the indirect-fired approach proposed herein.

At a commercial scale of operation and with the higher electricity prices that exist outside of British Columbia (Option 3), the financial analysis indicates that the incremental investment in the electric generation portion of the system provides very attractive rates of return.

PHASE III (In progress)

Canadian Resourcecon is currently proceeding with Phase III of the indirectly-fired gas turbine cogeneration project. The overall goal of Phase III is to organize and structure a demonstration project for the type of system investigated in Phases I and II. In order to accomplish this general goal, Phase III has the following objectives:

1. Identify specific sites and industrial participants for which the system would be attractive.

2. Investigate and identify sources of funding for a demonstration project, including private, provincial, and federal sources.

3. Work with an engineering firm and equipment suppliers (turbine or heat exchanger manufacturers) to form a consortium which could engineer and build a system of this type.

4. Structure an agreement as the basis for proceeding with a project to demonstrate the technical and economic viability of the indirectly-fired gas turbine cogeneration system.

REFERENCES

Canadian Resourcecon Ltd. 1987, 1988. Woodwaste-fuelled, indirectly-fired gas turbine cogeneration plant for sawmill applications. Phase I: Preliminary engineering design and financial evaluation. Phase II: Site-specific engineering and financial analysis.

P4-8

DEVELOPPEMENT ET EVALUATION DE SYSTEME DE RECIRCULATION DES GAZ DE CHEMINEE POUR UN CALORIFERE A COMBUSTIBLE SOLIDE

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CRIQ, QUEBEC

DEVELOPPEMENT ET EVALUATION DE SYSTEMES DE RECIRCULATION DES GAZ DE CHEMINEE POUR UN CALORIFERE A COMBUSTIBLE SOLIDE

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Deux systèmes de recirculation des gaz de cheminée ont été essayés sur un calorifère à bois. Les gaz froids étaient aspirés par un ventilateur à la sortie de l'échangeur de chaleur et réinjectés soit à l'arrière de la fournaise soit à l'avant. Les performances des deux systèmes ont été évaluées d'après la Norme CSA-B-415. L'injection des gaz à l'arrière de la fournaise n'a pas eu tellement d'effet, alors que l'autre système diminue les émissions totales de polluants d'environ 50%. Avant de pouvoir utiliser cette technique, on devra toutefois solutionner le problème de l'encrassement du système; la recirculation de gaz chauds pourrait peut-être atténuer ce problème.

Two flue gases recirculation systems have been tested on a warm air wood furnace. Cold flue gases were extracted by a fan at the exit of the heat exchanger and injected either at the back of the combustion chamber or at the front of it. Performance evaluation was based on CSA Standard B-415. Injection at the back of the furnace did not have much effect whereas the other system reduced pollutant emission by 50%. However, before using this technique one will have to solve the problem of recirculation system fouling up; hot gases recirculation might attenuate this problem.

INTRODUCTION

Le présent projet a été réalisé dans le but de déterminer expérimentalement si l'on peut améliorer de façon significative la performance d'un calorifère à air chaud à combustible solide en recirculant les gaz de cheminée. En pratique, une amélioration de performance est définie comme étant une diminution des émissions de polluants mesurés en grammes par mégajoule d'énergie nette produite.

L'hypothèse de base consiste à dire que si l'on peut, au moyen d'un système mécanique quelconque, ramener les gaz de cheminée dans la chambre de combustion, ceux-ci pourront brûler de façon plus complète et ainsi permettre une diminution de la quantité de polluants rejetés à l'atmosphère en même temps qu'une augmentation de l'efficacité énergétique du calorifère.

Pour vérifier cette hypothèse, deux systèmes de recirculation ont été conçus et testés tour à tour sur un calorifère. Dans les deux cas, les gaz de cheminée étaient captés à la sortie de l'échangeur et ramenés dans la chambre de combustion; dans la partie arrière dans le cas du premier système et dans la partie avant dans l'autre cas.

Tout le programme expérimental a été réalisé en utilisant un calorifère de marque "Newmac" modèle WB-100E. Tous les essais ont été conduits conformément à la norme préliminaire ACNOR-B415 M1986 en tenant compte des changements proposés par le rapport CRIQ FAB-85-099 [1] pour rendre les procédures de la dite norme utilisable dans le cas d'un calorifère.

RESULTATS

Avec recirculation des gaz à l'arrière de la chambre de combustion (figures 1 et 2), il n'a pas été possible d'améliorer la performance du calorifère. Après deux essais à débits différents, il est apparu évident que ce système ne donnerait pas de résultats intéressants.

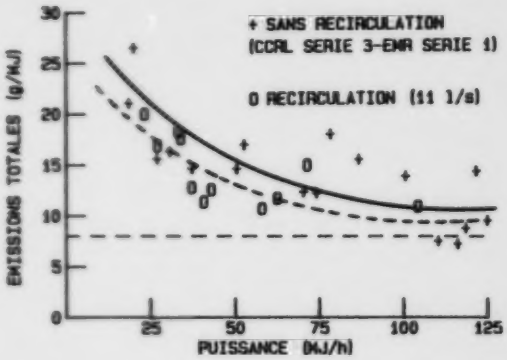

Figure 1 Recirculation à l'arrière de la chambre de combustion

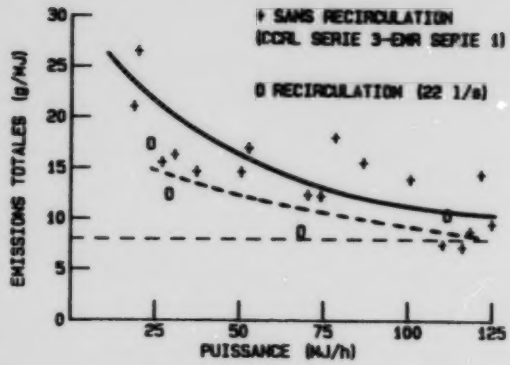

Figure 2 Recirculation à l'arrière de la chambre de combustion

Avec recirculation des gaz de cheminée à l'avant de la chambre de combustion (figures 3, 4 et 5), la performance du calorifère a pu être améliorée sensiblement. En fait, les émissions ont été réduites de moitié environ pour atteindre des valeurs voisines de 8 g/MJ. C'est donc dire que le calorifère mis à l'essai pourrait tout juste respecter une règlementation fixant le niveau maximum d'émissions permises à 8 g/MJ en utilisant un système de recirculation.

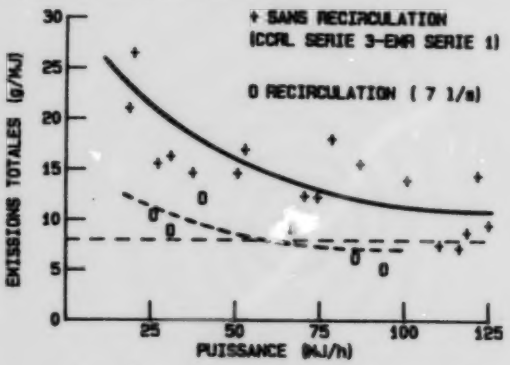

Figure 3 Recirculation à l'avant de la chambre de combustion

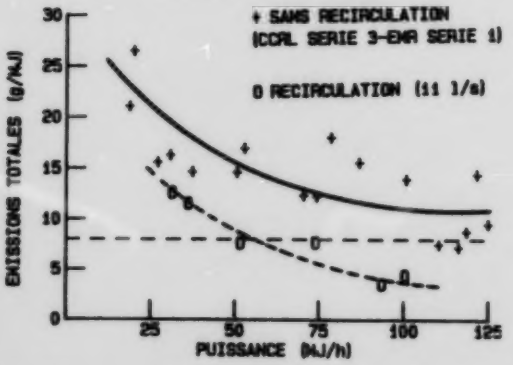

Figure 4 Recirculation à l'avant de la chambre de combustion

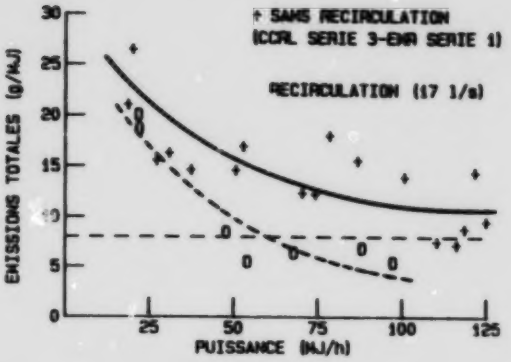

Figure 5 Recirculation à l'avant de la chambre de combustion

DISCUSSION

En examinant les résultats obtenus avec le système de recirculation à l'avant, puisque c'est celui qui a donné des résultats intéressants, on constate que le débit de gaz recirculé constitue une variable très importante du système. D'après les courbes, il apparaît qu'il existe un débit pour lequel on obtient une performance optimale; au-dessus de ce débit les performances sont moins bonnes.

De fait, la recirculation à débit élevé permet une diminution importante des émissions à haute puissance (figures 4 et 5) mais a moins d'effet à basse puissance. Comme c'est à faible puissance que les niveaux d'émissions sont les plus importants, il est clair que c'est dans cette région de la courbe qu'il faut obtenir de bons résultats. Lorsque l'on atteint le débit recirculé optimum (figure 3), les émissions sont réduites dans toute la gamme des puissances.

Ce phénomène pourrait s'expliquer par le fait qu'en augmentant le débit recirculé, on provoque un refroidissement de la zone de combustion ce qui est de nature à réduire la performance. Par contre, si le débit recirculé est trop faible, on se rapproche des conditions sans recirculation.

Selon cette explication, il serait sûrement intéressant de faire des essais en recirculant les gaz chauds; c'est-à-dire, pris à l'entrée de l'échangeur du calorifère. Le débit recirculé pourrait être augmenté sans que la zone de combustion ne soit refroidie indûment. On pourrait donc s'attendre à obtenir des performances améliorées. Qui plus est, l'échangeur du calorifère devrait demeurer plus propre à cause de la diminution des produits condensables avant évacuation.

REFERENCE

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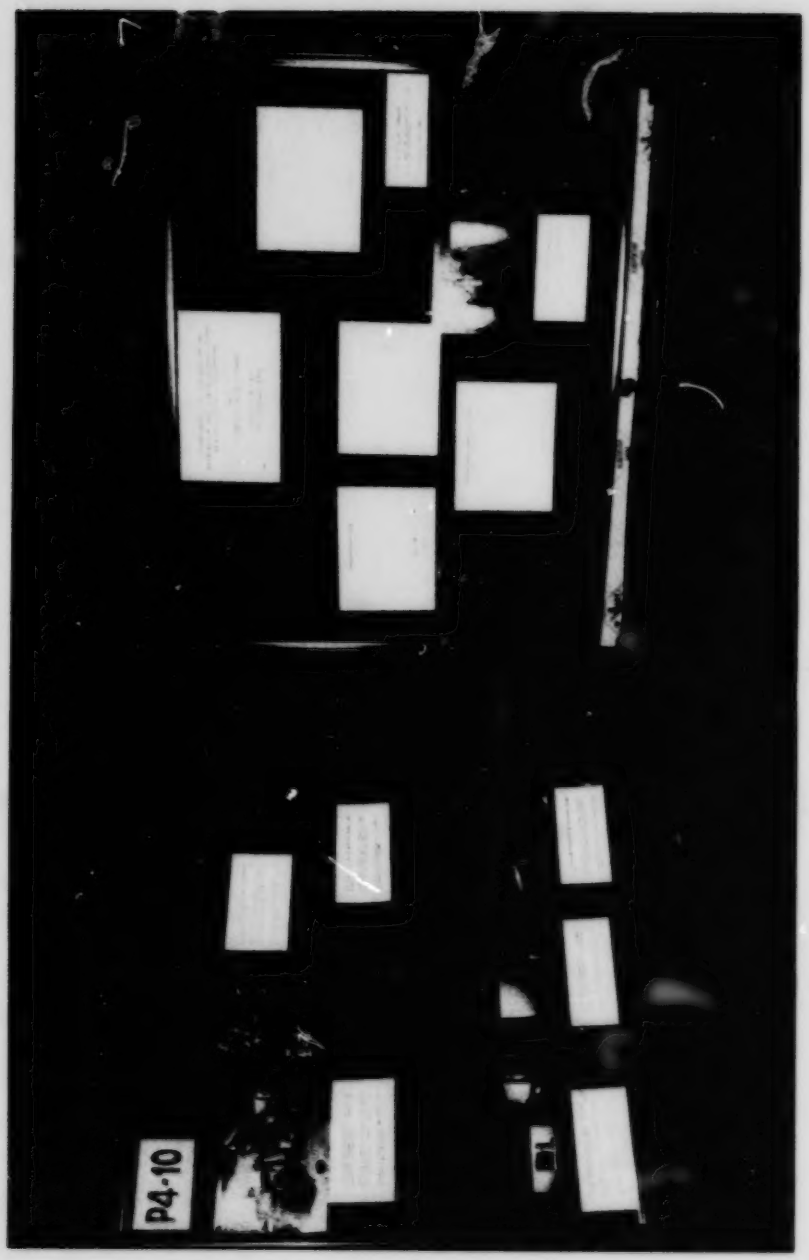
P4-10

TESTING PEAT IN THREE WOODSTOVES AND TWO PARTICULATE FUEL BURNERS

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Combustion tests were conducted with Newfoundland peat on three woodstove types and two particulate fuel burners. The objectives were to determine the combustion characteristics of the different appliances using peat at various moisture contents.

Preliminary testing with particulate fuel burners gave excellent results. Initial test results with woodstoves indicated that emissions were more dependent on moisture content than on woodstove type.

Des essais de combustion ont été effectués sur de la tourbe de Terre-Neuve dans trois types de poêles à bois et deux brûleurs à combustible particulaire. Le but de ces essais était de déterminer les caractéristiques de combustion des différents appareils en utilisant de la tourbe présentant divers taux d'humidité.

Les essais préliminaires réalisés avec les brûleurs à combustible particulaire ont donné d'excellents résultats. Les résultats des essais préliminaires effectués avec les poêles à bois ont indiqué que les émissions dépendaient de la teneur en humidité de la tourbe et non du type de poêle à bois utilisé.

INTRODUCTION

Over fifty percent of Newfoundlanders burn wood to satisfy some or all of their space heating needs. Large portions of Newfoundland are covered with peat bogs where few trees grow. Peat replaces wood as an alternative fuel in many homes on the Southern Avalon Peninsula.

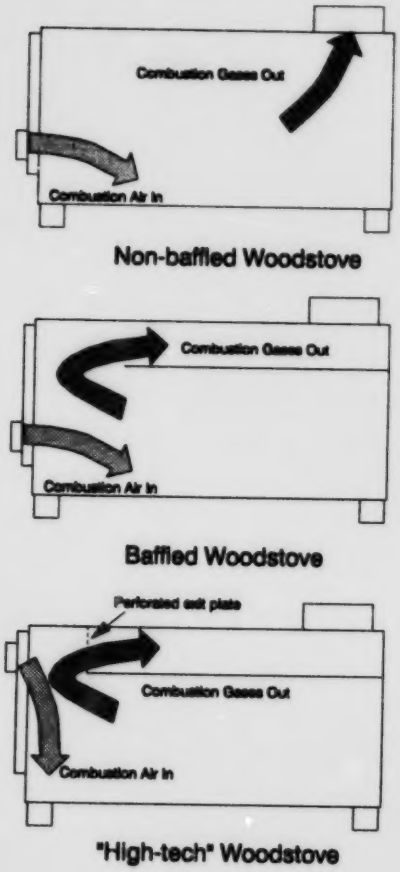
Peat is harvested during the summer months and formed into long cylindrical sods by extrusion machines. The sods are left on the fields to air dry. They are turned over periodically to accelerate drying. The harvested peat is stockpiled and sold to commercial distributors who bag it for resale.

For space heating applications the peat is usually burnt in woodstoves. Recent technology developments have produced stoves that burn wood with increasingly lower emissions. Do these high-tech appliances also burn peat with lower emissions? How does drying the peat affect emissions levels? This study attempted to answer these questions.

THE TEST APPLIANCES

Woodstoves: Three types of woodstoves were chosen for the emissions testing: a Chaleureux non-baffled, a Lakewood baffled and a Kent high-tech woodstove. These three types are representative of the woodstove technology which exists today, catalytics excluded.

Different woodstove designs



Pellet stove: The Volcanic Glow pellet stove was also chosen. Basically its design incorporates an auger which moves pellets from a storage bin to burn in a cast iron retort in the combustion chamber. Forced combustion air is supplied to the retort.

Particulate fuel burners: Two particulate fuel burner types used were a Swebo pre-heater and TP2000 stoker. The stoker and a pre-heater differ in that the pre-heater has its own separate combustion chamber. The stoker usually has an open bowl or pot and its burning takes place inside the structure of the heat exchanger.

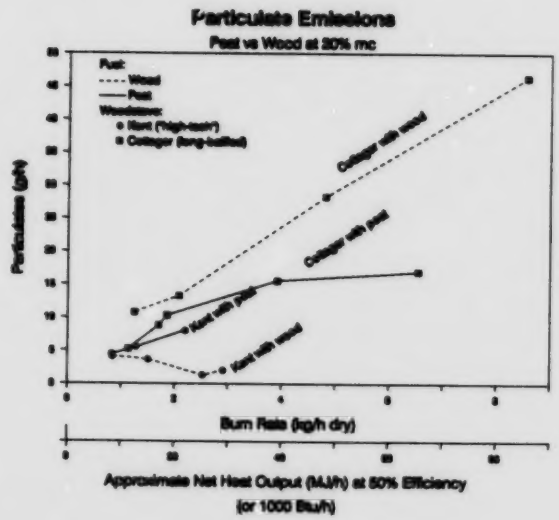
Both appliances require connection to a heat exchanger which is usually a warm-air furnace or boiler.

RESULTS

Particulate emissions

Note: the major problem of this study was the determination of moisture content of peat sod fuel.

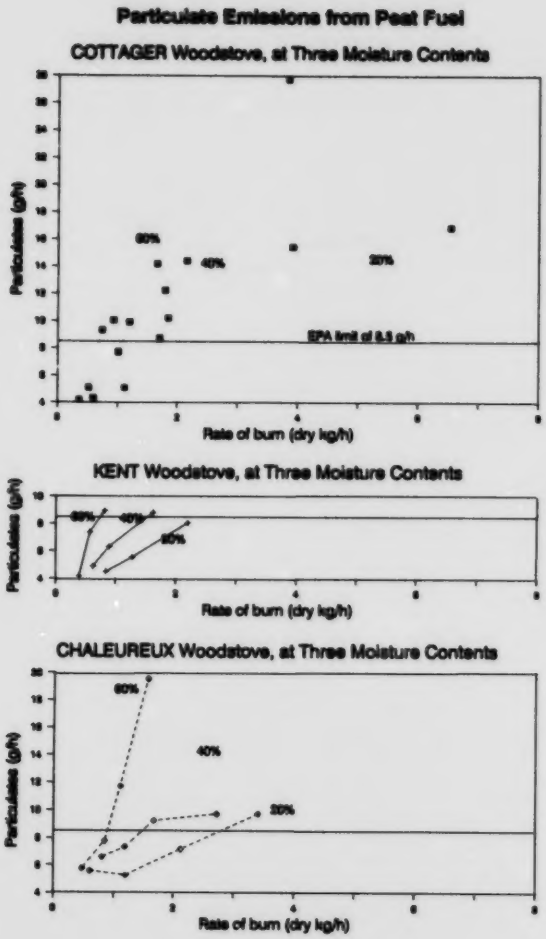
Graph 1



Particulate emissions of woodstoves: wood vs peat sods, at 20% m.c. (Graph 1)

- the "high-tech" woodstove (Kent) burns wood with much lower emissions than the long-baffled woodstove, at similar burn rates.
- however, when burning peat, the "high-tech" stove burns with approximately the same emissions level as the baffled stove.

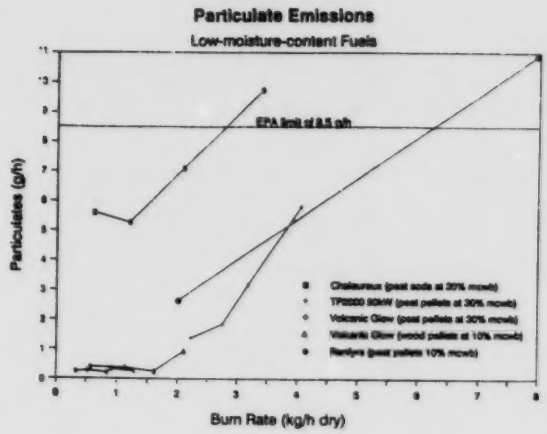
Graph 2



Particulate emissions of woodstoves burning peat sods at different moisture contents (Graph 2).

- with all woodstove types, emission levels (in g/h) increase with moisture content.
- with all woodstoves types, emission levels (in g/h) increase with burn rate.
- only the "high-tech" stove maintains low emission levels for all moisture contents, over its operating range. Its maximum output is 25 MJ/h (24,000 Btu/h) which is considerably lower than those of both the baffled and non-baffled stoves.

Graph 3



Emissions levels of particulate fuel burners burning peat: (Graph 3)

- the Volcanic Glow pellet stove burns both peat pellets and wood pellets with very low particulate emission levels. Its heat output would be appropriate for a house with a heat load peaking at 30 MJ/h (29,000 Btu/h).
- the TP2000 50 kW burns peat with low particulate emissions when compared to sods burned in a woodstove. Output from both appliances peak at approximately 100 MJ/h (95,000 Btu/h).
- the Swebo has a difficult time burning peat pellets because of the continued accumulation of ash on top of its fuel.

CONCLUSIONS OF OVERALL STUDY

1. Drying peat sods to 20% can reduce fuel consumption by 20 to 25%.

2. Drying peat sods can bring about a substantial decrease in particulate emissions.

3. Peat sods burn with higher efficiency in baffled and high-tech woodstoves than in "old" stoves.

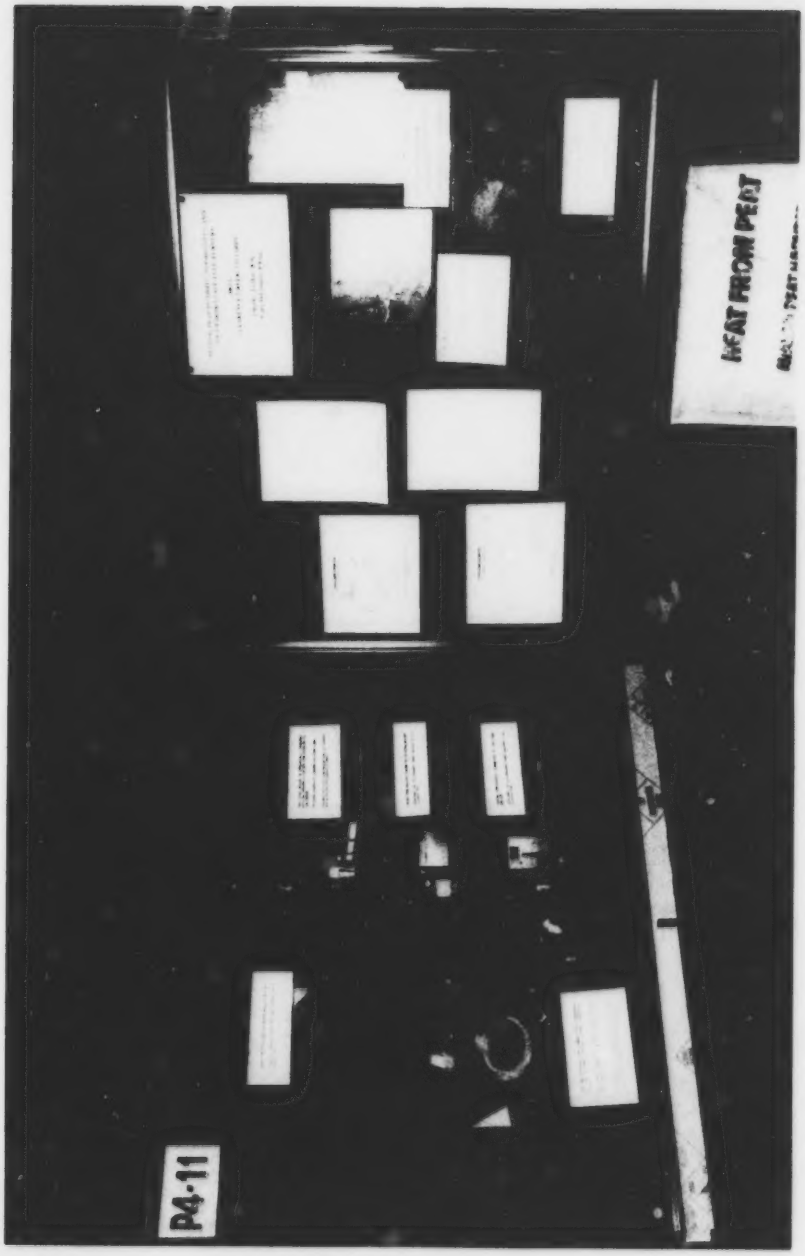
4. Pellet burning appliances can burn peat with very low emissions.

5. Pellet burning appliances can be designed to burn peat with efficiencies of 75%. These efficiencies are 50% higher than those obtained when burning peat sods in woodstoves and thus reduce fuel consumption by 1/3.

6. Although some particulate fuel burners can burn pelletized peat, pellet stoves and furnaces perform this specialized function much better.

7. Appliance emissions regulations should relate to heat output, not time, because the use of g/h forces the use of several small appliances whereas use of a single, larger appliance could well reduce the total emissions coming from a building.

8. The use of sod peat to heat homes in Newfoundland could result in 3 tonnes of particulates per year per 100 houses. The corresponding figure for peat pellets would be 90 kg; for oil, less than 3 kg; for a roundwood furnace, from 6 to 15 tonnes; and for a TP2000 30kW woodchip stoker, 600 kg.


P4-11
HEAT FROM PERT

ESTABLISHMENT OF CRITERIA FOR THE RETROFIT OF CHIP STOKERS TO ROUNDWOOD-BURNING FURNACES AND BOILERS

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Tests were conducted on 7 small particulate fuel burners ranging in size from 25 to 75 kW. These appliances were coupled to a variety of wood furnaces and boilers which were used as heat exchangers. Tests were conducted with a variety of fuel types and moisture contents. The objective of the study was to determine the compatibility of the retrofit combinations for safety, efficiency and environmental pollution.

The burner/heat exchanger retrofits operated without any major problems and were capable of low particulate emissions. Most of these burners gave excellent results in the handling and combustion of screened wood chips and pelletized fuels.

This study has shown that biomass waste can be burned efficiently and economically with very low atmospheric emissions.

On a effectué des essais sur sept petits brûleurs à particules dont la taille variait de 25 à 75kW. Ces appareils ont été reliés à divers fours et chaudières à bois qui servaient d'échangeurs de chaleur. Les essais ont porté sur divers combustibles, présentant des taux d'humidité variés. L'objectif de l'étude était de déterminer la compatibilité des appareils combinés en ce qui concerne la sécurité, le rendement et la pollution de l'environnement.

Les combinaisons brûleurs-échangeur de chaleur ont fonctionné sans donner lieu à des problèmes majeurs. Il a été possible de réduire à un faible niveau l'émission de particules. La plupart de ces brûleurs ont donné d'excellents résultats pour ce qui est de la manutention et de la combustion des copeaux de bois triés et des combustibles pellétisés.

Cette étude a montré que les déchets de biomasse peuvent être brulés efficacement et économiquement en libérant très peu de particules dans l'atmosphère.

INTRODUCTION

Many people fear the impact of increased biomass heating on our remaining decimated forests. However, they do not realize the enormous volumes of low-grade forest material and forest products industry residues that are available for combustion. Also, if the junkwood is removed from a forest for fuel production, the productivity of the forest can be improved.

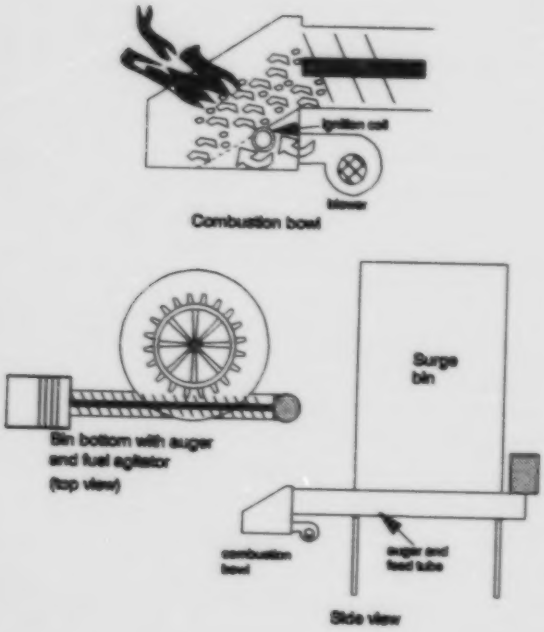
Small domestic particulate fuel burners, a technology which emigrated from Europe, have brought a new dimension to woodburning. These burners are capable of burning wood with much lower emissions and operate automatically.

This paper presents a general summary of the emission levels of particulate fuel burning systems and shows how they are dependent on the type of stoker or pre-heater, the heat exchanger, burn rate, fuel type and fuel preparation.

NOMENCLATURE

Stoker: a mechanical device that feeds particulate fuel into a combustion chamber. Burning takes place inside the structure of the heat exchanger. The stoker requires connection to a heat exchanger which is usually a warm-air furnace or boiler. A stoker may include a grate or a retort or a combustion bowl.

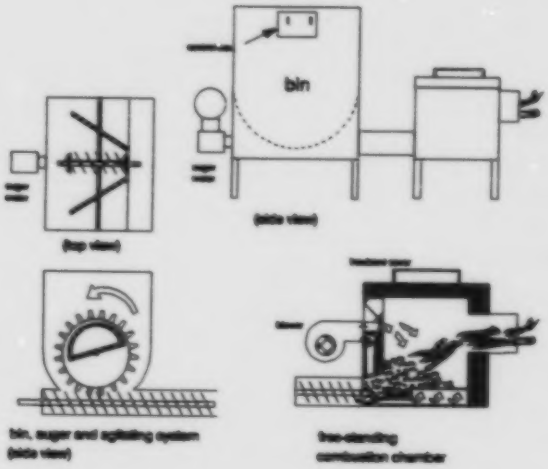
Vallsta Stoker



Stoker system: means a complete central heating appliance that consists of two units - a stoker and a compatible combustion-chamber/heat-exchanger assembly. Both units are supplied as an integrated central heating appliance by a single supplier and may or may not be fabricated by the same manufacturer.

Pre-heater: means an appliance which includes a stoker and a free-standing, or at least separate, combustion chamber. The stoker supplies particulate fuel to the combustion chamber where the fuel is burned completely. The pre-heater requires connection to a heat exchanger which can, in some cases, be a suitably modified warm-air furnace or boiler.

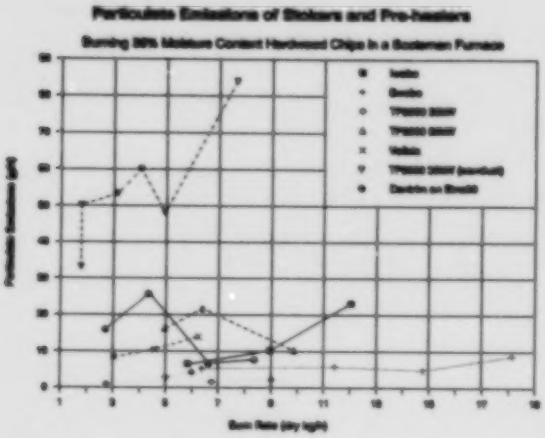
Swebo Pre-heater



Pre-heater system: means a complete central heating appliance that consists of a pre-heater and a compatible heat exchanger. Both units are supplied as part of an integrated central-heating appliance by a single supplier and may or may not be fabricated by the same manufacturer.

RESULTS

Graph 1



Stokers vs pre-heaters (Graph 1)

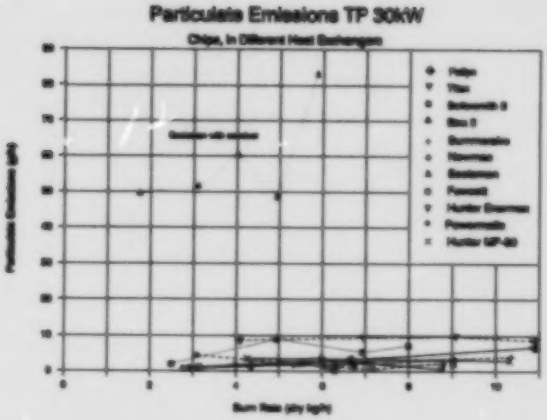
Most particulate fuel appliances burn cleanly with sawmill chips. The emissions from several of these are below the EPA (United States Environmental Protection Agency) limits of 8.5 g/h.

Emission levels indicate that pre-heaters (Swebo, Iwabo) burn cleaner than stokers (TP50, Vallsta) with sawmill chips. The smaller, enclosed combustion chambers on pre-heaters provide a hotter combustion environment than the open stoker bowls sitting inside a large, often uninsulated furnace. The TP30, although classified as a stoker, has an enclosed combustion tube. This tube acts much the same as the independent combustion chamber on pre-heaters and gives similar results.

From the above data, we can conclude that, at least for wood chips, it is better to have an enclosed combustion chamber than an open combustion bowl. The closed combustion chambers on the TP30 and on the Swebo produce low emissions. The open combustion bowls on the TP50 and the Vallsta produce higher emissions.

Emissions levels for a TP30 burning sawdust (49% mc) have been added on this graph as a comparison. These levels are typical of emissions from most compact, moist fuels such as whole-tree chips and ground bark. Perhaps the most remarkable information on Graph 1 is the fact that emissions from the Swebo remained below the EPA limits until the burn rate increased beyond the 16 kg/h (approximately 200,000 Btu/h). This is equivalent to the combined burn rate of approximately 6 to 8 "average" stoves.

Graph 2

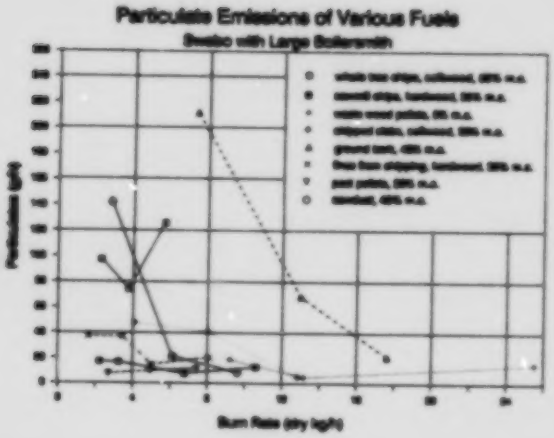


How heat exchangers influence emissions (Graph 2)

Emissions from the TP2000 30 kW stoker are only slightly influenced by the type of heat exchanger used when burning hardwood chips at 35% mc. The TP30 emission levels are low with all heat exchanger types although we note a small increase in emissions with two boilers, the Titan and the small Boilersmith. For comparison, we have included emissions from the combustion of sawdust at 49% mc in the Scotsman.

We have shown that pre-heaters tend to have a cleaner burn than stokers. Pre-heaters have more control over the environment in which combustion takes place. This makes them less dependent on the type of heat exchanger. On the other hand, stoker combustion takes place within the heat exchanger and this makes the stoker more dependent on the heat exchanger than the pre-heater. This influences the choice of heat exchangers for stokers. For these areas where the flames enter the firebox must be small and insulated.

Graph 3



How fuels influence emissions (Graph 3)

In this study we burned eight different fuels in a Swebo pre-heater coupled to a large Boilersmith boiler. Emission levels vary considerably with fuel type and with burn rate.

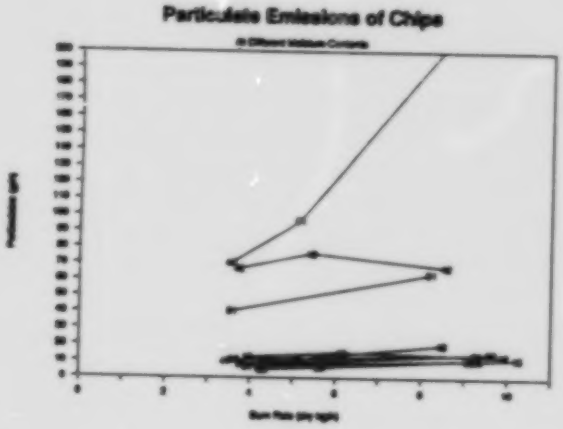
Sawmill chips, waste wood pellets and peat pellets burn with fairly low particulate emissions over a wide range of burn rates. Emissions from peat pellets were low but still appeared as black smoke, even at this low level.

Emission levels from whole-tree chips, sawdust, ground bark and fines from chipping are high. They are all compact fuels. Finer particles fill in the voids between larger pieces. Combustion under-fire air cannot be fed through the fuel but is restricted to the edges of the pile. To compensate for the poor burn, more excess air must be supplied to the poorly-burning fuel.

These compact fuels also can have a higher moisture content than the wood from which they originated. If exposed to rain, they soak up water easily. This high moisture content also tends to raise emission levels caused by fuel compactness.

At higher burn rates it is interesting to note that both sawdust and ground bark can burn with much lower emissions levels. Only at these higher feed rates does the Swebo's combustion chamber reach high enough temperatures to maintain proper combustion. Each of these fuels was fed until the maximum burn rate was reached. Past these maximum burn rates (feed rates), more fuel was being supplied to the combustion chamber than it was possible to burn. The combustion then became oxygen-starved. For example, in Graph 2 sawdust reaches its maximum sustainable rate at 5 kg/h (11 lb/h) on the TP30. Above this rate fuel is not completely burned and emissions rise quickly.

Graph 4



How moisture content inffluences emissions (Graph 4)

A fuel's moisture content influences its combustion characteristics. This can be clearly seen from Graphs 4. In this graph each line represents one batch of fuel that is fed at 3 different feed rates. Clean combustion is lost somewhere between 40 and 50% mc As moisture content of the fuel increases, heat production is reduced. This reduction is first due to an increase in the amount of energy necessary for evaporation of water. This reduction is compounded by the decrease in combustion efficiency at high moisture contents. In simpler terms, we have more water to boil and less fuel to make it boil, because some of the fuel is going up in smoke. These observations apply strictly to variations in moisture content in hardwood chips burned in the Swebo pre-heater. Other pre-heaters may behave similarly at similar moisture contents.

CONCLUSIONS OF OVERALL STUDY

1. Most stokers and pre-heaters tested gave good handling and combustion results with screened chips and pelletized fuels. Some pre-heaters could handle all non-compact fuels: screened and unscreened chips, pellets, peat chunks.

Particulate fuel burners have been found capable of very low particulate emissions. Their levels were often below the maximum permissible 1988 level of 8.5 g/h imposed on woodstoves by the EPA in the United States.

2. No appliance gave good combustion results with fuels such as sawdust, chipper fines, and whole tree chips where the fine material fills the interstices among the larger pieces of material, and thus prevents proper mixing with oxygen, i.e. it prevents turbulence.

3. Fuel delivery unreliability is one of the major problems with particulate fuel burners.

While stokers and pre-heaters are very efficient burners of biomass fuel and offer several advantages over their furnace and woodstove counterparts, their feed systems are still incapable of guaranteed delivery of chips to the combustion zone. We experienced occasional jamming of particulate fuel in the augers, and bridging of fuel in the surge bins.

4. It is difficult to design a particulate fuel burner that will handle the many variations in size and moisture content of particulate fuels.

Incompatibility between the fuel and the feed mechanism causes many problems. Pelletized fuels, because of their size and uniformity, are ideally suited to particulate fuel burners. They cause little or no feed problems. They can be handled by much smaller motors and augers. For the same energy output, pelletized fuels can be as economical as hardwood chips.

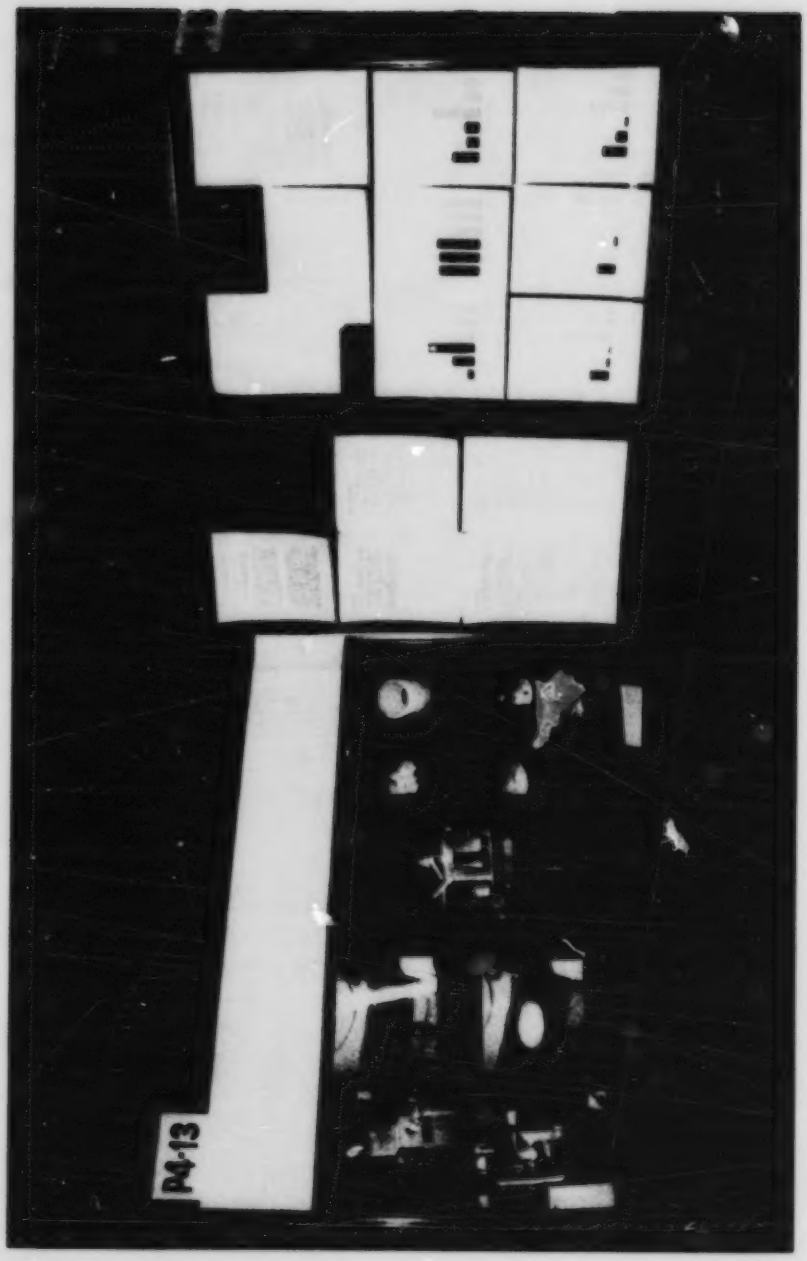
5. Arbitrary choice of a furnace or boiler for coupling to a stoker or pre-heater can create a mismatch, robbing the system of efficiency and increasing its emissions.

This can transform a good stoker into an uneconomical appliance. Testing has shown that many existing wood furnaces and boilers are not ideal choices for use as heat exchangers with particulate fuel burning appliances.

6. Most burners tested presented no high-fire problems for their own components or for those of the attached heat exchanger. However, the use of drier fuels or more energy-dense fuels, could result in the development of higher temperatures.

On two burners, control circuits were positioned too close to the combustion area.

7. All combustors had potential burnback problems.


P4-13

REDESIGN, CONSTRUCTION AND TESTING OF AES FURNACE

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The original AES central wood chip fired hot air furnace assumed a combustion rate of 5,000 Btu/hr/sqin of combustion chamber floor, but was only capable of 25% of this firing rate. The unit has been scaled up to achieve the required firing rate of 85,000 Btu/hr (90,000 KJ/hr). This has required the complete redesign of the combustion chamber and the feed system.

Le taux de combustion de l'appareil original de chauffage central à air chaud AES, alimenté par des copeaux de bois, devrait être de 5000 Btu/hr/po^2 de sole de la chambre de combustion, mais l'appareil ne pouvait atteindre que 25% de ce taux. Nous avons modifié l'appareil en vue d'augmenter ce taux à la valeur requise de 85,000 Btu/hr (90,000 KJ/hr). Pour ce faire, nous avons complètement modifié la chambre de combustion et le système d'alimentation.

Summary

The project has produced the required hot air furnace which burns wood chips.

The unit has a net thermal ouput of 90,000 KJ/hr required with a hot air rise of 47 deg C. It is automatic, maintains its fire through periods of low demand and needs to be fuelled at the most at 24 hour intervals.

It has performed well under CSA B415 Performance testing and will shortly be assessed under CSA B366.1 Safety Standard for Solid Fuel Appliances.

Introduction

Parrsboro Metal Fabricators purchased from the fabricator a sample of the AES chip fired furnace. This was used as a starting point for this project.

In order to produce a furnace to match the contract requirements of 90,000 KJ/hr (85,000 Btu/hr) net output with 24 hour fuel capacity and the ability to stay alight during normal cyclic operation, the development has required the following work:

1. The entire unit was scaled up by a factor of 3. The maximum net heat output of the AES unit as received from Maine was 26,000 KJ/hr, much lower than anyone expected.

2. The combustion chamber was redesigned from first principles. The scaled up combustion chamber would not burn properly either as scaled up or when modified in keeping with its original design. The method by which the combustion air was introduced did not maintain proper combustion.

3. The heat exchanger was redesigned from first principles to provide ash and fallout handling. The original heat exchanger had no provision for handling wood ash and its design promoted fouling of the heat exchange surfaces.

4. The AES unit was designed to burn 1/2" oak chips and we have identified a reliable auger system for handling the larger quantities of C4 and larger chips commonly available in Eastern Canada.

Unit Description

For ease of fabrication and handling, the unit was redesigned in 3 parts.

1. Bin and feed auger

   Provides 24 hours of metered fuel

   The bin has the capacity to operate the unit for 24 hours at a continuous burn rate of 90,000 KJ/hr.

   The fuel is metered by the bin auger, whose speed can be controlled by the furnace operator, to the transfer auger.

2. Transfer Auger

   Transfers fuel to furnace and provides a fire break in the fuel handling system.

   Allows system to be orientated horizontally to give compact bin and furnace arrangements.

3. Furnace

Provides up to 90,000 KJ/hr of heated air with a temperature rise of 47 Deg F.

Fire maintained during idle cycle with boosts of air and fuel at regular intervals.

Designed to operate in a similar way to a standard residential oil furnace.

Large door for initial lighting and cleanout.

Provides ash fallout collection and stabilised draft.

Approximate dimensions 1220 mm long x 1220 mm high x 500 mm wide.

Development Stages.

1. Unit was scaled up by a factor of 3 to provide the required output.

2. Combustion chamber was redesigned from first principles.

3. Heat exchanger was designed from first principles.

4. Ash collection was provided.

5. Auger and bin systems were redesigned to handle chips larger than C4 (1-1/2" to 2").

6. Optional power venter was installed to ensure stable chimney draft and combustion air.

7. Unit was tested to B415.

Performance Testing to CSA B415

The unit has been tested for performance using the principles of B415. This standard describes a procedure for measuring the gaseous and particulate emissions and the efficiency of the unit.

The unit was tested at three fuel rates using fresh green fuel and dry fuel. The results are summarised in the table below.

Test Conclusions

The following conclusions can be drawn from these results.

1. Dry chips performed better than wet chips: Efficiencies were higher and particulate and gaseous emissions were lower.

2. Higher feed rates produce higher efficiencies and lower particulate emissions. Gaseous emissions were also generally lower.

3. The dry chips fed at a lower rate than the wet chips for any given motor setting. This was due to their larger chip size of the dry fuel and the presence of twigs.

4. The dry fuel produced 86,698 KJ/hr of heat with the best overall performance at the highest fuel rate.

Table of Test Results.

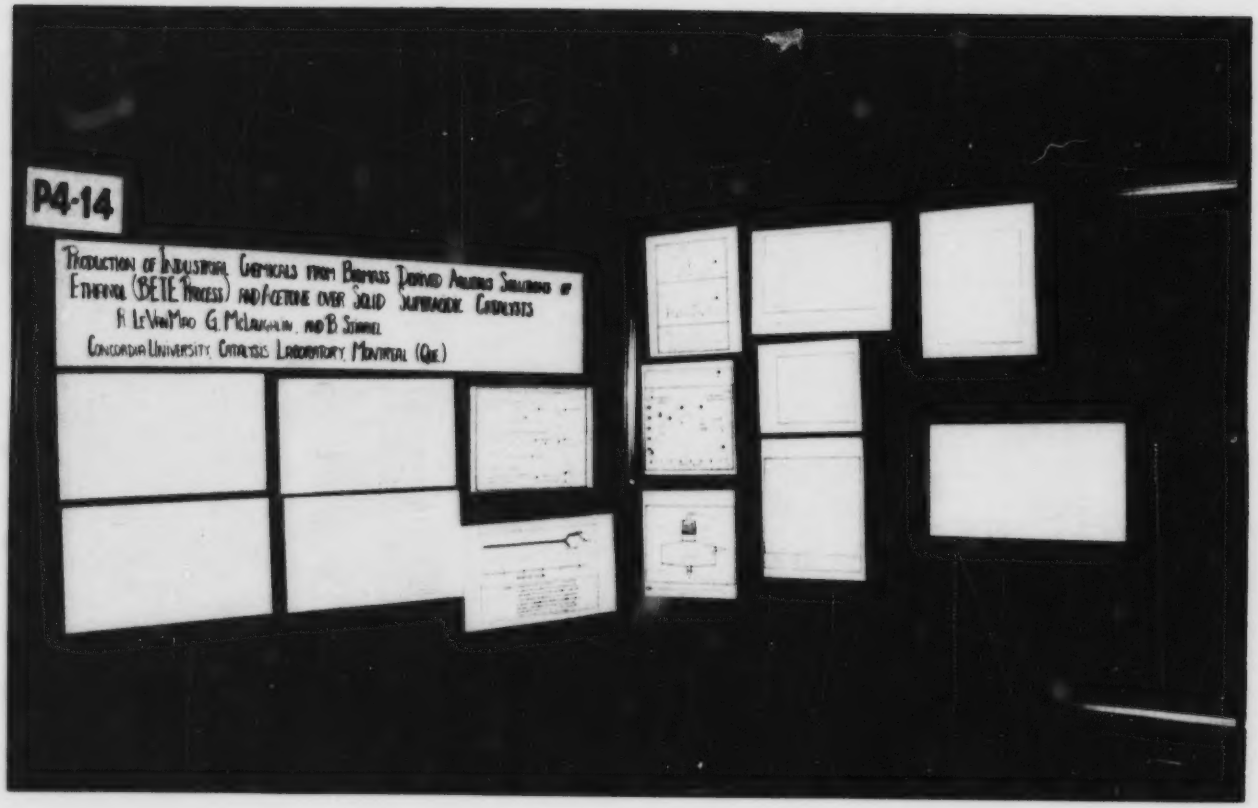
Test no.	1	2	3	4	5	6
Mode	idle	low	high	idle	low	high
Rate Kg/hr	1.2	3.8	8.2	1.5	9.1	11.0
% M.C	16.4	16.4	1.64	40.9	40.9	40.9
% CO	.08	.04	.01	.10	.06	.06
% O2	16.98	16.17	13.76	17.48	16.35	14.4
% CO2	3.81	4.34	6.6	3.39	4.12	5.79
Stack deg C	82.82	160.6	169.7	73.3	142.7	192.5
Amb deg C	23.5	23.1	22.5	21.1	22.2	23.2
Air rise deg C	36	47	47	36	47	47
Input Kg/hr	15,124	58,467	127,709	14,512	89,804	116,774
Output KJ/hr	9,862	39,022	86,698	6,744	51,543	70,896
Efficiency %	65.2	66.7	70.6	46.4	57.4	60.7
CO gm/hr	17.97	31.95	12.87	20.99	72.79	72.61
HC gm/hr	40.44	6.55	54.18	75.08	104.2	31.94
Part gm/hr	9.09	4.09	4.82	16.56	5.33	5.67
CO gm/MJ	1.82	0.82	0.15	3.11	1.41	1.02
HC gm/MJ	4.10	0.17	0.62	11.26	2.02	0.45
Part gm/MJ	.92	0.10	0.06	2.46	0.10	0.08
CO gm/Kg fuel	14.98	8.41	1.57	13.99	8.00	6.15
HC gm/Kg fuel	33.7	1.72	6.61	50.59	11.45	2.71
Part gm/Kg fuel	7.57	1.08	0.59	11.04	0.59	0.48
Test no.	1	2	3	4	5	6

Project Results.

The project has produced the required hot air furnace which burns wood chips.

The unit has a net thermal output of 90,000 KJ/hr required with a hot air rise of 47 deg C. It is automatic, maintains its fire through periods of low demand and needs to be fuelled at the most at 24 hour intervals.

It has performed well under CSA B415 Performance testing and will shortly be assessed under CSA B366.1 Safety Standard for Solid Fuel Appliances.


P4-14
Production of Industrial Chemicals from Biomass Derived Aqueous Solutions of Ethanol (BETE Process) and Acetone over Solid Supracidic Catalysts
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PRODUCTION OF INDUSTRIAL CHEMICALS FROM BIOMASS DERIVED AQUEOUS SOLUTIONS OF ETHANOL (B.E.T.E. PROCESS) AND ACETONE OVER SOLID SUPERACIDIC CATALYSTS

R. Le Van Mao, G. McLaughlin and B. Sjiariel

Concordia University, Catalysis Laboratory, Montreal (Quebec)

ZSM-5 and Y-types zeolites treated with triflic acid, an organic superacid, exhibit unusual catalytic properties: extremely high acidic character, high product shape selectivity and high thermal/hydrolytic stability. Aqueous solutions of ethanol and acetone (with concentration ranging from 5 to 10 wt%) are selectively converted with very high yields into ethylene and light olefins/aromatics, respectively, at reaction temperatures as low as 200°C. The high thermal stability of the catalysts derives probably from the strong chemical bonding (H bonds) of the adsorbed triflic acid molecules with the zeolite protonic acid sites. The enhanced shape selectivity of the solid superacidic catalysts is due mainly to pore size modifications upon loading of the triflic acid.
Preliminary economical evaluation of the Bioethanol-to-Ethylene (B.E.T.E.) process shows a very promising future for the conversion of biomass into the very commercially valuable ethylene.

Les zéolites de type ZSM-5 et Y qui ont été traitées à l'acide triflique, un superacide organique, possèdent des caractéristiques catalytiques inhabituelles, soit un caractère extrêmement acide, une selectivité élevée eu égard à la forme/géométrie des produits et une stabilité thermique/hydrolytique élevée. Des solutions aqueuses d'éthanol et d'acétone (dont la concentration varie de 5 à 10 %) sont sélectivement transformées, avec des rendements très élevés , en éthylène et en oléfines légères/hydrocarbures liquides , respectivement, à des températures de réaction aussi faibles que 200 °C.
La stablilité thermique élevée des catalyseurs dérive des fortes liaisons chimiques entre les molécules d'acide triflique et les sites protoniques de la zéolite. La sélectivité de forme accrue des catalyseurs superacides solides découle principalement des modifications qu'accuse la taille des pores pendant le traitement à l'acide triflique.
L'évaluation économique préliminaire du procédé bioéthanol à éthylène (procédé B.E.T.E.) montre que la conversion de la biomasse en éthylène, produit présentant une grande valeur commerciale, possède un avenir très prometteur.

INTRODUCTION

Ethanol is currently produced by hydration of ethylene which is derived mainly by steam-cracking of petroleum or natural gas feedstocks. Ethanol can also be obtained by the anaerobic fermentation of sugars (mostly glucose) which can be "extracted" from various biomass materials. However, the competitiveness of such a bioethanol with respect to the petroethanol is regularly the subject of discussion.
In our laboratory, zeolite catalysts which allow the production of practically pure ethylene from aqueous ethanol (concentration of ethanol in the

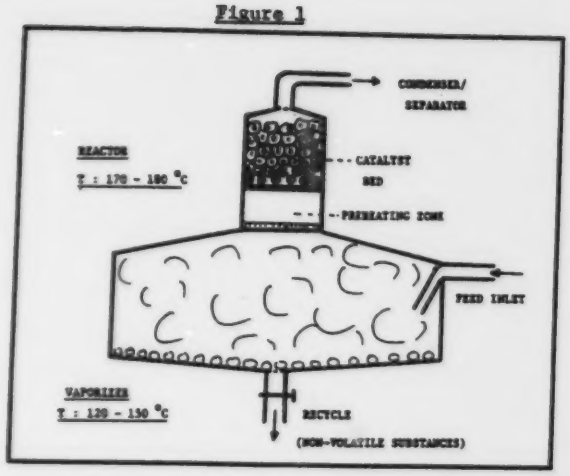
aqueous solution ranging from 2 to 19 vol %) have been developed (1 - 6). This also means that ethylene can be produced directly from various ethanol fermentation broths in a one-step process (called B.E.T.E. or Bioethanol-to-Ethylene) (6).

The latest version of these catalysts, a superacidic ZSM-5 zeolite, can catalyse the reaction at temperatures as low as 170 °C and under atmospheric pressure (6).

Moreover, such superacidic catalysts can convert a very dilute aqueous solution of acetone (2 - 15 vol %) in hydrocarbons (light olefins and other liquid products) (7).

This paper summarizes the main results so far obtained in our laboratory when an aqueous solution of ethanol or acetone is sent over these solid superacidic catalysts.

Figure 1



LABORATORY REACTION SYSTEM FOR THE BIOETHANOL-TO-ETHYLENE PROCESS

EXPERIMENTAL

The hydrothermal synthesis of ZSM-5 zeolites and asbestos-derived zeolites (the so-called chryso-zeolites), and their conversion into the acid catalysts were reported elsewhere (8-10). The preparation of the superacidic zeolites and chryso-zeolites were described in some recent papers, patent applications and technical reports (4-7, 11).

Solid superacidic catalysts were characterised by numerous techniques (6,7,11) including various vapor sorption measurements.
Catalytic testing was performed at first in a tubular reactor (1 - 7, 11) and then in a special B.E.T.E. reaction system (6,11)(see Figure 1).

RESULTS AND DISCUSSION

Pure triflic acid (trifluoromethane sulfonic acid) or TFA starts boiling at 162 °C whereas this organic superacid when incorporated into the ZSM-5 zeolite structure is thermally stable up to 300 °C, as shown by thermal gravimetric analysis (6). Hundreds of catalytic runs performed in the presence of aqueous solutions of ethanol or acetone have shown no

CATALYST	ETHANOL CONVERSION (wt %)	PRODUCT SELECTIVITY (wt%)	
		ETHYLENE	OTHER HYDROCARBONS
NAFION NR-50	12.0	100	——
ALUMINA (ACIDIC)	0.0	——	——
H-Y/TFA (a)	43.4	93.8	6.2
Silicalite/ TFA (a)	13.7	99.6	0.4
H-ZSM-5 (Si/Al: 10)	14.0	99.8	0.2
H-ZSM-5/TFA (a),(Si/Al: 10)	97.3	99.9	0.1
H-ZSM-5/TFA (a), (Si/Al: 21)	95.8	97.7	2.3
H-ZSM-5/TFA (a), (Si/Al: 54)	72.0	98.1	1.9

Table 1: CATALYTIC PERFORMANCE OF THE TFA ZEOLITES
(a) : 2 wt % - Reaction conditions: T: 200 °C; Feed : 10 wt% ethanol in water; W.H.S.V. : 1.0 h^{-1}

significant loss of the TFA component below 250 °C, even in the massive presence of water in the feed.

Table 1 reports the catalytic performance of the TFA modified ZSM-5 zeolites having various Si/Al atomic ratio values. The lower the Si/Al ratio, the richer the zeolite surface in terms of protonic acid sites, and as reported in Table 1, the more performing and the more stable the catalyst. This is due to the synergy " TFA - zeolite" , and probably to the existence of hydrogen bonds between the TFA molecules and the zeolite surface protons (see Figure 2).

On the other hand, the TFA coating of the ZSM-5 zeolite surface reduces considerably the zeolite pore size, and thus enhances significantly the product shape selectivity of the catalyst. Figure 3 reports the yield in ethylene and the adsorption capacity with respect to n-hexane, vs. the TFA loading. The amount of adsorbed n-hexane(having the same molecular size as ethanol, but a non polar character) decreases with increasing TFA loading whereas the yield in ethylene passes through a maximum at 4.0 wt %.

The use of the specially designed reactor (Figure 1) allows the production of practically pure ethylene directly from the ethanol fermentation broth. Moreover, it also permits the production of a heavy syrup which contains left-over glucose, some yeast residues and yeast nutrients (inorganic salts). This provides some interesting by-product credit for the bio-ethylene, since the obtained heavy syrup can be used as fertilizer or as nutrient additives to animal food.

The B.E.T.E. process requires a net process energy which is only 20 % of that of a conventional two stage distillation (of ethanol from the fermentation broth).

Our (preliminary) estimates (6) gives a figure of 0.375 $ / kg of ethylene produced by the B.E.T.E. process (see also Table 2). This production cost is 30 % higher than that of ethylene produced from petroleum or natural gas feedstocks in certain Western countries.

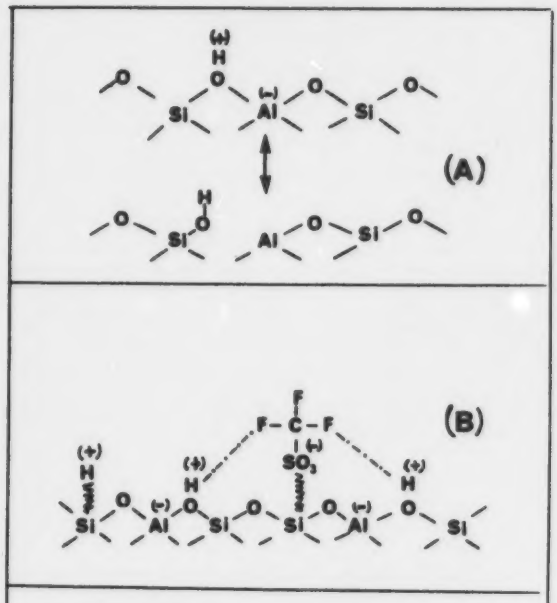


FIGURE 2:
(A) ACID SITES ON THE ZEOLITE SURFACE
(B) DISSOCIATIVE ADSORPTION OF TRIFLIC ACID AND STABILIZATION OF THE ADSORBED SPECIES BY FORMATION OF HYDROGEN BONDS

FIGURE 3 : EFFECT OF TRIFLIC LOADING ON THE ETHYLENE YIELD (—●—) AND (—□—) AND THE N-HEXANE ADSORPTION (-·-·-✱-·-·-)

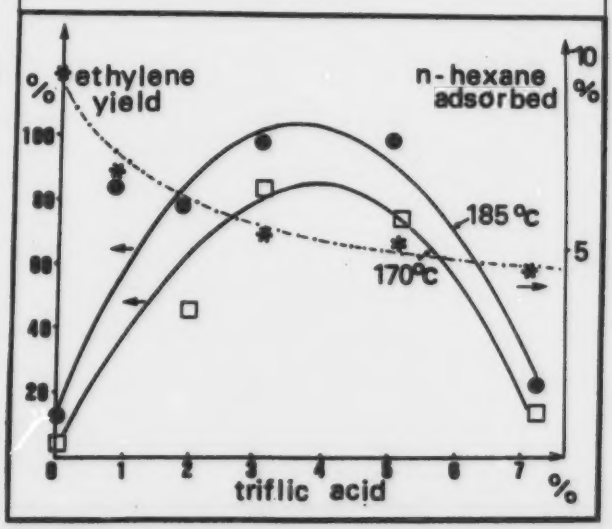


Table 2 PRODUCTION COST ESTIMATES (April 1988, in U.S. dollars) (6)

ETHYLENE FROM THE B.E.T.E. PROCESS:

- Raw material: wood wastes or agricultural residues
- Production cost assumed for fermentation ethanol : $ 0.25/l (or Can $ 0.31/l)
- Production cost of unpurified fermentation broth which contains 1 liter of recoverable ethanol : $ 0.21
- Final production cost of ethylene: $ 0.17/lb or $ 0.375/kg

ETHYLENE FROM PETROLEUM OR NATURAL GAS DERIVED FEEDSTOCKS:

Selling price (April 1988): $ 0.24/lb

Estimated production cost:

$ 0.16/lb - $ 0.11/lb or $ 0.35/kg - $0.24/kg

CATALYST	H-ZSM-5/ TFA (2)	H-Y/TFA (3)
Total acetone conversion (C %)	87	85
Product selectivities (PS %)		
Hydrocarbons	71.1	53.1
Acetic acid	5.9	13.5
Propionic acid and other acids	12.1	---
Other O-compounds	1.3	trace
CO_2, CO	9.5	33.4
Hydrocarbon selectivities (HCS %)		
Ethylene	1.79	0.18
Propylene	8.54	8.02
Isobutene	35.03	10.75
n-butenes	8.75	2.39
C_1-C_4 Paraffins	2.46	32.38
C_5 - C_9 aliphatics	41.72	21.97
Aromatics	1.72	4.32

Table 3 Catalytic data of the H-ZSM-5/TFA (2) and the H-Y/TFA (3) catalysts (Reaction temperature : 235 °C (508 K), W.H.S.V.: 0.1 h^{-1}, aqueous solution of acetone : 9 wt %).

However, the following factors will reduce this difference in the medium-long term range:

- Ethylene demand and price continue to increase;
- Ethylene production cost in some countries is increasing ;
- Substantial progress is expected in the hydrolytic step within the entire process from biomass or cellulosic materials (increasing by-product credit);
- Renewable biomass is abundant in some countries at very low cost.

The TFA modified ZSM-5 zeolites can convert acetone in very dilute aqueous solutions to light olefins and propionic acid, mainly (Table 3). The main products obtained with such acetone feeds are light paraffins and acetic acid when TFA modified Y-type zeolites are used as catalysts. The change in product yield and selectivity with respect to the parent ZSM-5 and Y-type zeolites can be explained again by the enhanced acidity and shape selectivity of the zeolites with the triflic acid loading (7).

CONCLUSION

Ethylene and other valuable light olefins (isobutene, for instance) can be produced by reacting aqueous solutions of ethanol and acetone, respectively, over solid superacidic catalysts. The reaction is carried out at 200 °C, and there is practically no need for prepurification or predistillation of the fermentation broth.

ACKNOWLEDGEMENTS

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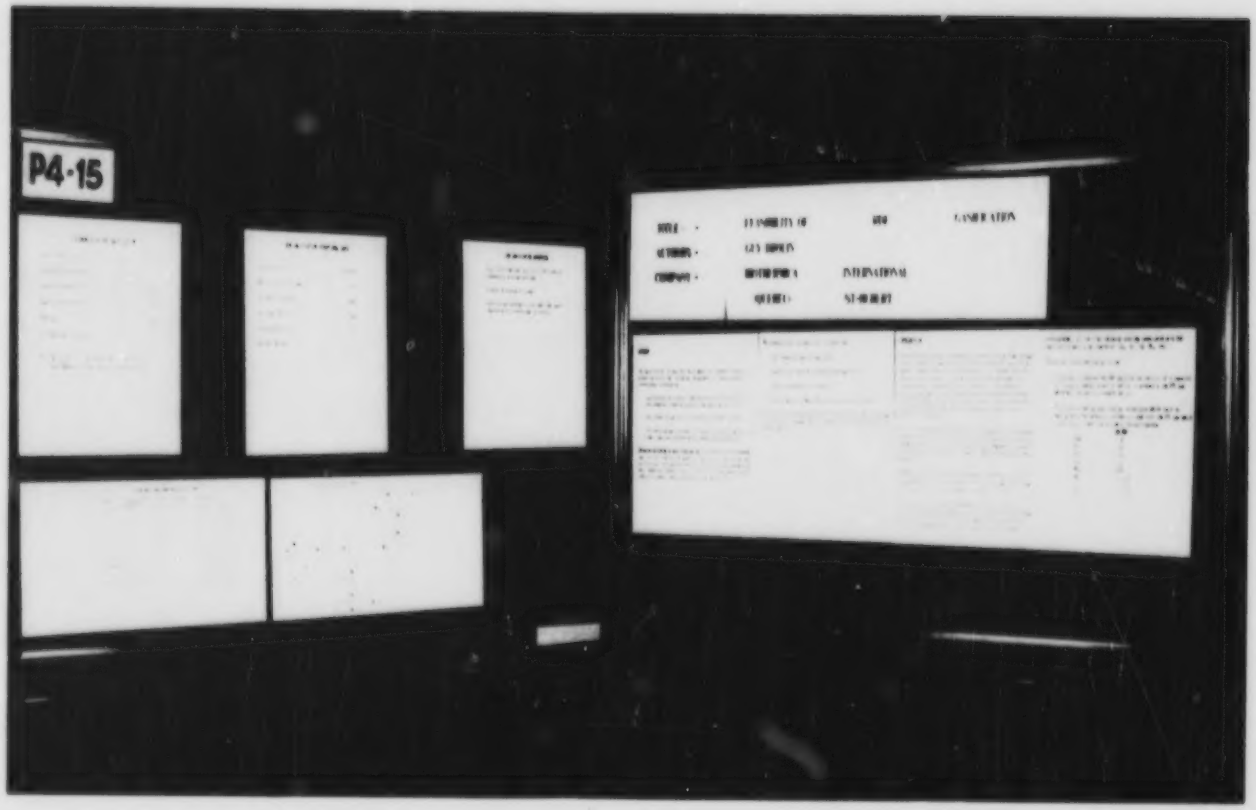
P4-15

GAZEIFICATION DES DECHETS MUNICIPAUX PAR LIT FLUIDISE

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Biothermica International Inc.
Saint-Hubert (Québec)

La gazéification des déchets municipaux aux fins de production d'énergie offre les avantages suivants par rapport à l'incinération classique:

- La gazéification permet de rencontrer plus facilement les normes environnementales les plus strictes en égard des émissions de gaz acides (HCl, SO_2).
- Le procédé de gazéification ne crée aucune production de dioxines et de furanes.
- Les coûts d'investissement et d'opération du gazogène sont inférieurs aux coûts de l'incinération classique.

Désourdy-Biothermica Gazéification Inc. propose une adaptation de la technologie de gazéification Biosyn dans le cadre de ce projet. Un système original d'épuration des gaz a été conçu par le groupe de façon à permettre au gaz de rencontrer les normes de l'industrie gazière. Une usine de 100 000 tonnes/an permettrait de produire quelques 100GJ/h d'énergie thermique et procurerait un rendement de l'ordre de 14% après impôt.

The gasification of municipal solid waste for purposes of energy production offers the following advantages in comparison with conventional incineration:

- Gasification facilitates compliance with even the strictest environmental standards on acidic gas emissions (HCl, SO_2).
- The process of gasification produces no dioxins or furans.
- The operating and investment costs associated with a gasifier are lower than those incurred with a conventional incinerator.

Désourdy-Biothermica Gazéification Inc. is proposing that the Biosyn gasification technology be adapted to this project. An original gas purification system was designed by the group to produce gas which will meet industrial characteristics. A 100 000 t/yr plant would produce 100GJ/h of thermic energy with an after tax IRR of 14%.

INTRODUCTION

Les incinérateurs de déchets municipaux ont été et sont encore un moyen d'élimination très fiable des déchets urbains. L'incinération contrôlée des déchets solides est en effet née de la nécessité de diminuer les volumes à enfouir et les nuisances reliées à l'opération d'enfouissement en territoire urbanisé (1). Cependant, du fait de l'évolution de la composition des ordures ménagères, l'incinération s'est révélée être une source majeure de pollution athmosphérique. En plus des matières particulaires, les fumées d'incinération contiennent beaucoup d'autres substances toxiques, tels les composés chlorés et fluorés, les métaux lourds, les dioxines et furanes.

Les réglementations environnementales européennes et américaines se renforcissent de plus en plus de façon à diminuer ces émissions athmosphériques à des niveaux certes techniquement réalisables, mais souvent très coûteux. Par ailleurs, les pouvoirs publics sont de plus en plus conscients des transferts possibles de pollution, où ce qui a été capté au niveau de l'émission, se retrouve dans un effluent à traiter, et dans des cendres qui, en se lixiviant lors de l'enfouissement, relachent les métaux toxiques lourds dans l'environnement. (2, 3)

Aussi, un intérêt grandissant est porté sur l'utilisation de nouvelles technologies de transformation des déchets municipaux en énergie, telle la gazéification.

AVANTAGES DE LA GAZEIFICATION

Les déchets municipaux sont d'abord convertis dans une usine de recyclage en combustible dérivé de déchets municipaux (CDDM). Cette portion est ensuite gazéifiée dans un réacteur en lit fluidifié du même type que celui mis au point par BIOSYN. Dans le cadre de l'implantation d'un centre de recyclage de déchets municipaux, il est prévu une importante production de combustible dérivé

de déchets municipaux (CDEM) qui pourrait soit être brûlé dans une cimenterie, ou gazéifiée, pour produire un gaz propre à faible pouvoir calorifique.

Les avantages de la gazéification par rapport à la combustion sont multiples.

1. Le procédé de gazéification permet de produire un gaz propre qui, mélangé au gaz naturel ou à l'huile peut facilement être brûlé en chaudière; ce même gaz peut alimenter une turbine à gaz pour produire de l'électricité.

2. Compte-tenu que le procédé de gazéification nécessite environ un volume d'air égal au tiers (1/3) de ce qui est prévu pour l'incinération, le système de nettoyage des gaz est plus compact et permet de rencontrer des normes atmosphériques beaucoup plus sévères que dans le cas de l'incinération classique.

3. Enfin, les coûts d'opération et de maintient d'une unité de gazéification et d'épuration des gaz sont moins importants que pour une unité d'incinération classique. (4, 5, 6,7).

En s'appuyant sur les développements récents de la technologie Rinsys, le groupe Désourdy-Biothermica Gazéification Inc. propose un système de gazéification et d'épuration des gaz pouvant rencontrer les normes présentées à la Figure 1.

Figure 1

	Mg/Nm³ Caractéristiques des gaz à la sortie
Matières particulaires	≤ 20
HCl	≤ 50
HF	≤ 1
NH_3, HCN, CN	≤115
H_2S, COS	≤150
NO_x	≤200
SO_2	≤ 50
Pb	≤ 0,10
Hg	≤ 0,10
Cd	≤ 0,05

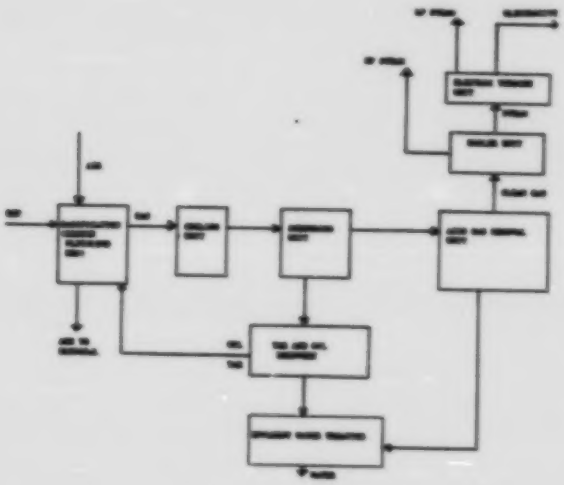
DESCRIPTION D'UNE USINE DE GAZÉIFICATION DE DÉCHETS MUNICIPAUX

L'usine proposée comprend quatre (4) sous-systèmes (Figure 2)

- Stockage et manutention du CDEM;
- Gazéification et enlèvement des cendres;
- Epurations des gaz et recirculation des goudrons;
- Traitement des effluents.

Pour produire quelques 50 GJ/hre d'énergie, il faut prévoir gazéifier environ 6 tonnes/hre de CDEM et se doter d'une usine d'une capacité annuelle de 50 000 tonnes/an de CDEM.

Figure 2
RDF GASIFICATION - BLOCK FLOW DIAGRAM
(Désourdy-Biothermica System)



Stockage et manutention du CDEM

Les caractéristiques moyennes du CDEM sont présentées à la Figure 3. Le système de stockage et de manutention du CDEM à partir de la pile extérieure comprend une trémie tampon d'une capacité de rétention de 2 heures et un système de convoyeur à courroie appropriés. Un électro-aimant empêche les pièces métalliques de s'introduire dans le procédé.

Figure 3
CARACTERISTIQUES DU CDEM

Densité (base sèche) (Kg/m_3)	64
Dimension moyenne (mm X mm)	50 X 25
Humidité (%)	20
Cendre (%)	12
Pouvoir calorifique supérieur (KJ/Kg)	17 400

Gazéification

De la trémie tampon, le CDEM est introduit dans un gazogène de type Bionyn au moyen d'un alimentateur qui possède comme caractéristique la particularité de former à son extrémité un bouchon étanche afin de prévenir les retours de gaz. Le bouchon est formé par l'action d'une vis sans fin qui force le mouvement du matériel contre un pointeau situé à son extrémité. Le matériel ainsi comprimé et sous pression est alimenté dans le gazogène à lit fluidifié à l'aide d'un convoyeur à vis.

Le gazogène à lit fluidifié opérant sous pression possède plusieurs caractéristiques avantageuses par rapport aux gazogènes conventionnels à lit fixe. (8, 9, 10,11)

- Le lit fluidifié maintient une température uniforme dans le gazogène, entraînant rapidement un équilibre dans les réactions chimiques complexes qui favorise la formation d'un gaz à composition stoechiométrique stable.
- Les hautes températures atteintes (800°C à 900°C) ont pour avantage de briser les molécules complexes de goudron, permettant la production d'un gaz plus propre.
- Le lit fluidifié permet un transfert de chaleur rapide et intime entre les diverses particules de bois, augmentant la cinétique des réactions chimiques de réduction du carbone et diminuant ainsi le temps de résidence des particules de bois dans le gazogène.
- La matière inerte de nature silicieuse composant le lit favorise les transferts thermiques entre les phases solide et gazeuse et permet une meilleure rétention de l'énergie dans l'enceinte du gazogène.
- Enfin, l'opération sous pression permet de confiner dans un espace réduit le processus de gazéification, diminuant ainsi les investissements.

La technologie Bionyn a été éprouvée dans deux (2) usines pilotes de taille industrielle, l'une situé au Québec et l'autre en Guyane Française. La Figure 4 présente l'expérience canadienne en gazéification.

Figure 4
EXPERIENCE CANADIENNE EN GAZEIFICATION

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	1	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	7	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	8	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	7	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	6	[illegible]

Système d'enlèvement des cendres en continu

Un système automatique d'évacuation des cendres est prévu au bas du gazogène afin de retirer tous les matériaux (verres, métaux, sables) ne pouvant pas être fluidisés.

ÉPURATION DES GAZ ACIDES

L'épuration d'un gaz produit par gazéification de CDEM est compliqué par le fait que ce gaz contient des contaminants solides, liquides et gazeux, à savoir:

- matières particulaires composées de cendres alkalines et de char non converti;
- goudrons lourds et légers, condensables et contenant des HPA (Hydrocarbures polyaromatiques);
- organiques divers, tels phénols, aérosols, napthalène, etc.;
- présence d'ammoniaque, (NH_3), de sulfure d'hydrogène (H_2S), etc.;
- présence de métaux lourds, tel le plomb (Pb), le mercure (Hg), le cadmium (Cd), etc.

Plusieurs options à la purification de ces gaz existent, en s'inspirant notamment des travaux accomplis sur l'épuration des gaz d'incinérateur et de gazogène au charbon. (14, 15)

Plusieurs voies peuvent être actuellement envisagés:

- voie sèche;

- voie semi-sèche;

- voie humide.

Il est essentiel d'avoir une approche globale et cohérente de l'épuration des gaz. Le fait d'épurer les gaz et d'éviter une pollution de l'air ne doit pas induire une nouvelle source de pollution au niveau de l'eau rejetée ou des déchets à évacuer. Il faut éviter un transfert de pollution.

La voie sèche pourrait comprendre les systèmes suivants:

- injection de chaux en continue dans le gazogène;

- épuration des gaz à chaud par éléments filtrant en céramique;

- crackage catalytique des goudrons.

Une telle approche est attrayante pour la production d'électricité par couplage d'un gazogène sous pression à une turbine à gaz. (16)

La voie humide inclue les éléments suivants, qui éliminent séquentiellement les particules, goudrons et contaminants organiques:

1. cyclones primaire et secondaire pour recirculer le char non converti et évacuer les cendres;

2. tours de lavage pour saturer le gaz avec l'eau et condenser les goudrons, les particules, et les métaux lourds;

3. échangeur de chaleur pour refroidir le gaz;

4. débrumiseur pour sécher le gaz;

5. tour d'absorption pour neutraliser les gaz acides.

Un système de recirculation des goudrons est prévu, de façon à les réinjecter dans la zone oxidante au bas du gazogène et augmenter l'efficacité énergétique du système.

La Figure 5 présente les caractéristiques typiques d'un gaz produit par gazéification du CDDM, avant et après le système d'épuration des gaz.

Figure 5

Caractéristiques du gaz (% mol)

	Sortie Gazogène	Sortie Epurateur
CO	12,3	12,8
CO_2	13,0	16,0
H_2	5,2	6,5
H_2O	23,6	6,4
CH_4	4,1	6,4
C_xH_y	1,6	2,0
N_2	41,1	51,0
NH_3 (ppm vol)	5 567	115,0
HCl (ppm vol)	1 485	50,0
H_2S (ppm vol)	803	150
Goudron (mg/Nm³)	9 400	1 800
Poussières (mg/Nm³)	15 000	20
PCS (MJ/Nm³)		5,5

ASPECTS ECONOMIQUES

Les aspects économiques du projet d'implantation d'une usine de gazéification de CDDM ont fait l'objet d'une analyse détaillée (Figure 6). Pour assurer un taux de retour sur l'investissement supérieur à 15% après impôt (IRR), les conditions suivantes devront être rempli:

1. Capacité de l'usine - supérieure à 100 000 tonnes/an

2. Prix vendant du gaz - supérieur à 3,90$/GJ

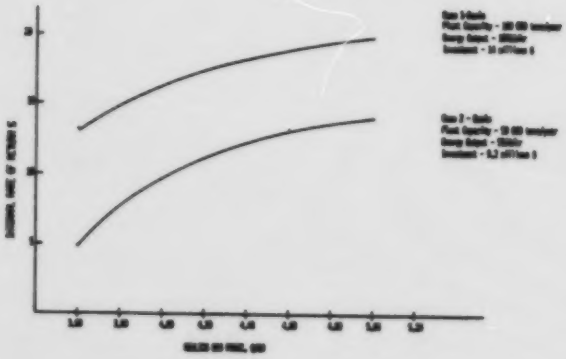
3. Production - supérieure à 8 000 heures/an, la deuxième année d'opération

4. Investissement - 14 millions $

5. Coût du CDDM - NIL

6. Subvention gouvernementale - 20% de l'investissement

Figure 6
ECONOMICS OF GASIFICATION



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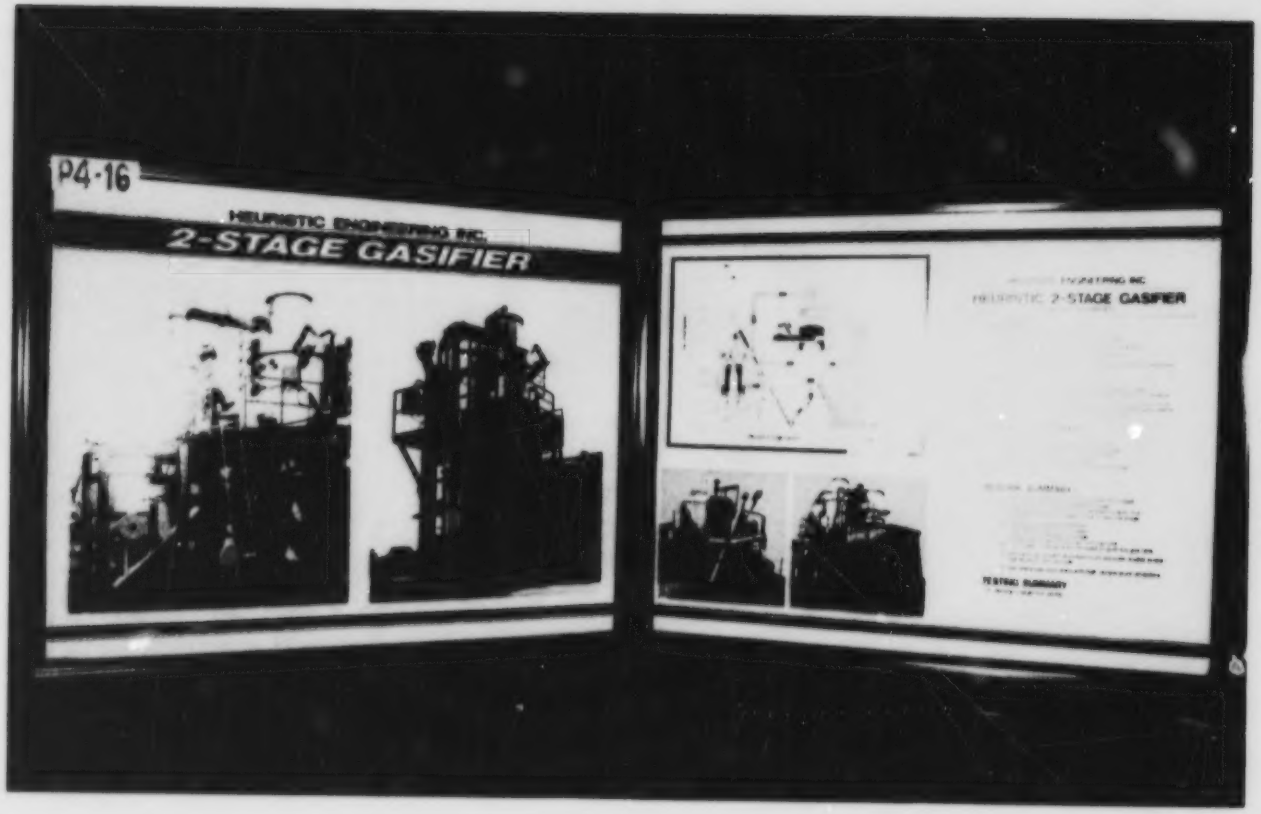
P4-16
HEURISTIC ENGINEERING INC.
2-STAGE GASIFIER
HEURISTIC 2-STAGE GASIFIER
TESTING SUMMARY

FURTHER DEVELOPMENT OF A WET WOOD TWO-STAGE GASIFIER

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A 3.2 GJ/hr (3 Million BTU/hr) prototype Heuristic 2-Stage gasifier is in the final stages of development. The wet wood gasifier is designed to gasify chips and hog fuel. An important application is the replacement of fossil fuels in pulp mill lime kilns at those pulp mills which have a surplus of hog fuel. Following completion of a 21 hour endurance acceptance test, carried out under earlier EMR contracts, the gasifier has been mechanically reworked. The rework involved the installation of gas seals and air locks to minimize leaks and to eliminate short circuiting of first stage gas down into the second stage. The present paper discusses the rework. Testing of the reworked gasifier will be carried out shortly.

Nous en sommes aux étapes finales de la mise au point d'un prototype de gazéificateur Heuristic à deux étapes,d'une capacité de 3,2 GJ/h (3 millions de BTU/h). Ce gazéificateur pour bois humide, qui a été conçu pour gazéifier les coupeaux de bois et les déchets de bois, possède une importante application: en effet, il permet de remplacer le combustible fossile utilisé pour alimenter les fours à chaux des usines de pâte et papier disposant d'un surplus de déchets de bois.
A la suite, d'un essai d'endurance d'une durée de 21 heures réalisé en vertu de contrats passés avec EMR, on a apporté au gaséificateur des modifications de nature mécanique, comprenant l'installation de joints étanches aux gaz et de sas, en vue de réduire au minimum les fuites et d'empêcher complètement les gas du premier étage de passer directement dans le second étage.
Dans cette communication, on examine les modifications apportées. Les tests du gazéificateur débuteront très bientôt.

INTRODUCTION

The Heuristic 2-Stage Gasifier has been reworked so as to isolate its first stage of updraft gasification from its second stage of downdraft char gasification. A rotary air lock was inserted between the two stages. To accomplish this it was necessary to move the second stage out from under the first and to install a screw conveyor to move char from the bottom of the first stage to the top of the second.

Three other air locks were also installed to isolate the gasifier from its environment. Air locks were inserted at the fuel inlet to the first stage, at the ash outlet from the second stage, and under the output gas clean-up cyclone. In addition to the air locks two sets of hot gas rotary seals were installed on the impeller shafts of the two hot gas fans to complete the isolation of the gasifier.

The rework also included:

i) a new, two piece, refractory-lined, scrolled, gas transition section above the repositioned second stage,
ii) a new, square, ash removal section below the cylindrical second stage, complete with a pair of ash removal screw conveyors which together feed a single ash discharge screw conveyor,
iii) the modification of the existing second stage to incorporate inner and outer diameter walls of high temperature refractory provided with many small air passages. A refractory-lined output gas collection plenum was also added which completely surrounds the lower portion of the original second stage,
iv) a new frame to support all the above.

THE REWORK

The Heuristic 2-Stage Gasifier was built by, repeatedly reworked by, and was tested on the site of, Brunette Machine Works Ltd of New Westminster, B.C. Five months after work began on the present contract Brunette sold their existing manufacturing facility and moved into smaller quarters. Unfortunately, there was no room for the gasifier on the new, smaller, site. Before leaving Brunette completed the fabrication of the various major components designed for the rework.

The new owners of the Brunette property granted Heuristic a five month grace period in which to find a new home for the gasifier. Five months later the gasifier was barged from New Westminster - along the Fraser River, out into the Gulf of Georgia and up into Burrard Inlet - to the North Vancouver yard of Versatile Pacific Shipyards Inc.

The gasifier was assembled in the shipyard. Figure 1 is a photograph of the reworked gasifier. Figure 2 is a flow schematic.

As can be seen from both Figures 1 and 2, the second stage, which was originally (1) directly under the first stage, has been moved out from under the first stage and over to left of this stage. The char air lock, which was installed to eliminate short circuiting of first stage gas (from the lower regions of the grate) down into the second stage, is shown at the bottom of the first stage.

The wood feed air lock, installed above the inlet to the screw conveyor feeding the first stage, the ash air lock, installed under the discharge of the ash removal screw conveyor, and the cyclone air lock, installed under the flare burner cyclone, can all be seen in Figure 2.

The impeller shafts of the two hot gas fans, seen in Figure 2 separated by a cast refractory venturi nozzle, are each fitted with a Circo-Flex, Inc (Cleveland, OH) dry, carbon-faced, mechanical seal. The seals consist of a stationary section (fastened to the housing), a rotating section (fastened to the shaft), and a spring-loaded floating section. The three sections are contained in a housing which is oil cooled with a heat transfer oil to protect the housing/shaft lip seal.

The refractory venturi nozzle, shown in Figure 2, was cast in a wood mold which had been turned to conform to ISA nozzle specifications. A thermocouple is installed in the throat of the venturi. The nozzle and its thermocouple are used to measure producer gas mass flow.

The refractory-lined transition section, above the reworked second stage, contains an internal gas passage of rectangular cross-section. The gas passage is shaped in the form of a volute of steadily decreasing area. As first stage gas spirals inwards the volute distributes the gas uniformly around the second stage. A series of nested stainless steel louvres is used to back pressure the volute.

The walls of the second stage are lined with high temperature refractory. They are pierced by many small diameter air passages through which gasification air is admitted. The air issues from internal and external plenums into the inner and outer diameter walls of the annular chamber.

A refractory-lined producer gas collection plenum was added around the existing second stage. A series of equally spaced holes, drilled in the former outer diameter wall of the second stage, admit producer gas to the refractory plenum. The holes back pressure the second stage so as to ensure uniform extraction of producer gas from around the periphery of the second stage annulus.

TESTING

Leak testing of the reworked gasifier has been completed. Performance testing will begin shortly. Air, producer gas and wood flow measurements will be made using the orifices and the producer gas venturi nozzle shown in Figure 2, as well as the four load cells mounted under the wood metering bin.

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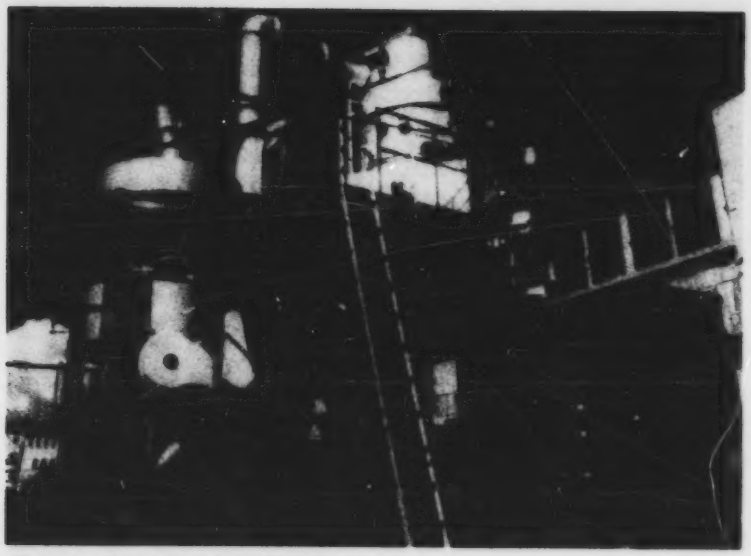

Figure 1 - Reworked 2-Stage Gasifier

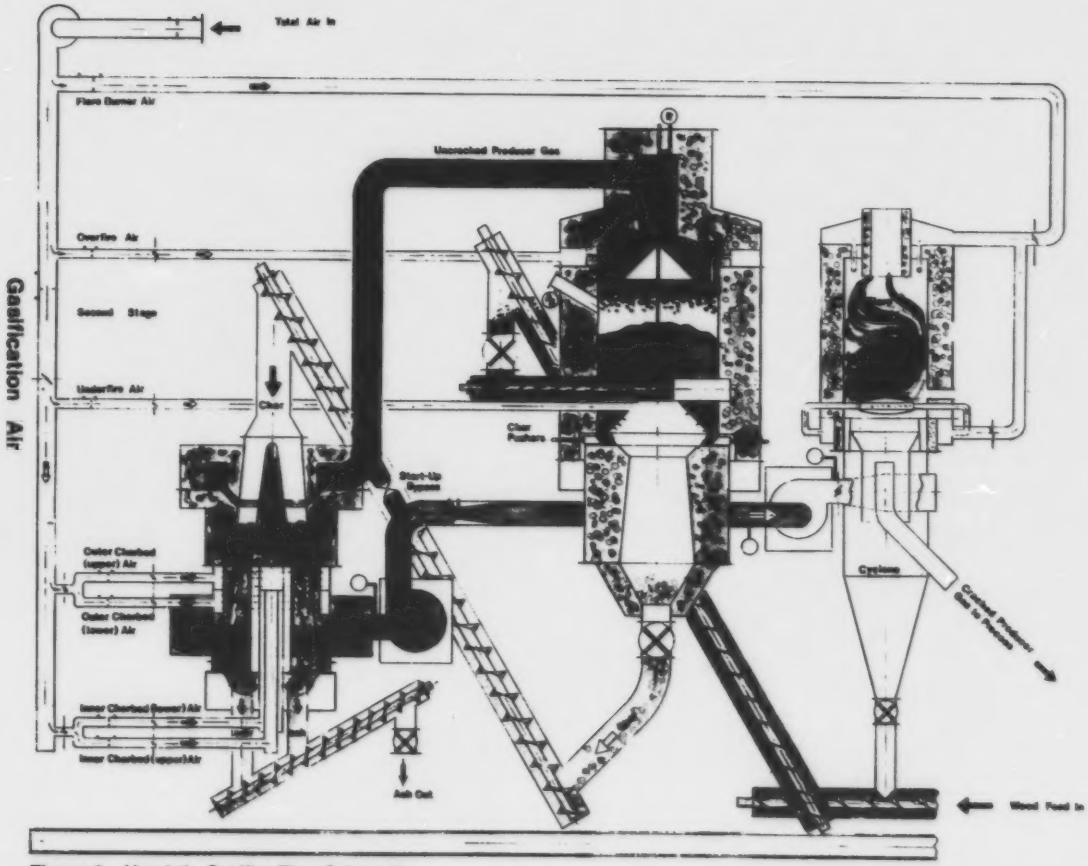

Figure 2 - Heuristic Gasifier Flow Schematic

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RESIDENCE TIME AND MIXING PATTERNS IN A FLUIDIZED BED GASIFICATION SYSTEM

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In a fluidized bed gasification system, the bed consists of inert particles of sand or alumina. The bed is supported by a distributor through which the gasifying medium is introduced. The gasifying medium maintains the bed material in suspended fluidized state. The high circulation of sand particles in the fluidized bed distributes the fuel particles rapidly throughout the bed. The fluidized bed gasification technology has been successfully applied for coal gasification. It offers several unique and versatile features for the efficient gasification of straw. However, biomass gasification is very much a complicated process. The products distribution in the bed is very sensitive to rate of heating and the residence time in the reactor. Thus, successful development of a fluidized bed straw - gasification system depends upon the thorough understanding of the complex mixing and fluidization phenomena occurring in the reactor. The objective of this paper is to discuss the mixing patterns, the fluidization and particles residence time in the cold bed as affected by four parameters. These are bed height, airflow rate, type of distributor and type of sand. Four bed heights, five airflow rates, five distributor plates and two types of sands were used in this study.

Dans les systemes de gazeification a lit fluidise, le lit, qui est constitue de particules inertes de sable ou d'alumine, est supporte par un diffuseur par lequel on introduit le milieu de fluidisation, c'est-a'dire le fluide qui maintient la matiere du lit en suspension. L'importante circulation des particules de sable dans le lit fluidise distribue rapidement les particules de combustible dans tout le lit. La technologie du lit fluidise a ete appliquee avec succes a la gazeification du charbon. Elle offre plusieurs caracteristiques uniques et polyvalentes pour la combustion et/ou la gazeification efficace de la paille. La gazeification de la biomasse est un porcede tres complexe. La distributiondes produits dans le lit est tres sensible au taux de chauffage et au temps de sejour dans le reacteur. Il faut donc posseder une tres bonne connaissance des phenomenes complexes de brassage et de gazeification qui interviennent dans le reacteur pour mettre au point un systeme a lit fluidise qui permette de realiser efficacement la gazeification de la paille. L'objectif de la presente communication est d'examiner les modes de brassage, la fluidisation et le temps de sejour des particules dans le lit froid et de determiner dans quelle mesure ces derniers sont modifies par la hauteur du lit, le debit d'air, le type de diffuseur et le type de sable. Au cours de cette etude, on a utilise quatre hauteurs de lit, le debits d'air, cinq plaques de diffusion et deux types de sable.

INTRODUCTION

Fluidized bed gasifiction technology is being applied to cereal straw. Effective gasification requires rapid mixing of straw with the inert bed material in order to obtain a uniform distribution of the fuel particles throughout the bed. Rapid contact between gas molecules and straw particles must also be achieved for better chemical conversion. However, mixing problems in fluidized bed systems become very severe when fuel particles vary both in size and density (Cranfield, 1978; Niewnow and Cheesman, 1980; Nienow and Naimer, 1980). Nienow et al. (1978) suggested that one of the main causes of segregation is the out of balance forces which arises during the periodic disturbances associated with the passage of the bubbles which are due to differences in density. The mechanism by which mixing occurs and the factors that determine mixing were studied by many workers (Yoshida et al., 1980; Jain and Sengupta, 1978; and Rowe and Nienow, 1976). Nienow and Rowe (1981) reported that particle mixing is caused solely by bubbles. Their studies showed that the degree of mixing depends upon physical properties of the particles such as density, shape, stickiness, size and size distribution as well as the condition of operation. Thus, data on mixing are far from complete and almost completely lacking for commercial units.

The gas distributor is one of the most critical

features in the design of a fluidized bed reactor. The studies by Sathiyamoorthy and Sridhar (1979) and Werther (1978) showed that the use of a suitable gas distributor is essential for satisfactory performance of gas-solid fluidized beds. Werther (1978) indicated that the understanding of solids mixing and flow characteristics of gases and solids near the grid region of a fluidized bed reactor is vitally important from the standpoint of design and scale up of gas distribution systems. The presence of stagnant zones near grid region can cause hot spots resulting in agglomeration and eventual reactor failure.

EXPERIMENTAL APPARATUS

The experimental apparatus used in this study is shown in Figure 1. The main component of the system are: (a) the air supply unit, (b) the fluidized bed reactor (c) the cyclone and (d) the pressure drop measurement system. With reference to Figure 1, the following are detailed descriptions of the system components.

Air Supply

The air was supplied to the bed by two different types of blowers, each was equipped with a filter, a pressure gauge, a main valve, a by-pass valve, an air line and a flow meter.

For fluidizingof the fine sand (μm 198), a small blower (220 volts and 4.9 amps) having a maximum flow rate of 2.04 m^3/min (72 cfm) was used. The blower was powered by a 1.0 HP single phase electric motor (Recenair Electric Motor, Gast MFG Corporation) and ran at a speed of 3450 rpm. The maximum pressure that could be obtained from the blower was 125 cm H_2O (1.22 kPa). For fluidizing the coarse sand (μm 536), a bigger blower (220 volts and 13.4 amps) having a maximum flow rate of 4.87 m^3/min (172 cfm) was used. The blower was powered by a 4.8 HP, 3 phase electric motor (Blador Industrial Motor) and ran at a speed of 2850 rpm. The maximum pressure that could be obtained from the blower was 212 cm H_2O (2.08 kPa).

A filter having a micron rating of 25 and a maximum flow of 7.08 m^3/min (250 cfm) was used at the blower inlet to filter the incoming air in order to supply dust and water free air to the system. A pressure gauge (USG) having a pressure range of 0-690 kPa (0-100 psi) with a scale of 13.8 kPa (2 psi) increments was used at the exit of the blower to check the pressure level in the air supply line in order to maintain atmospheric pressure in the bed. The main valve was used to control the air flow rate while the by-pass valve was used to by-pass the excess air to avoid over heating of the motor.

The air line, through which the air was supplied to the fluidized bed was composed of horizontal and vertical steel pipe sections. The horizontal section on which the flow meter was mounted was connected to a 600 mm long horizontal steel pipe having an inner diameter of 63 mm. This was connected to a 100 mm long vertical pipe by a 90° elbow having the same inner diameter.

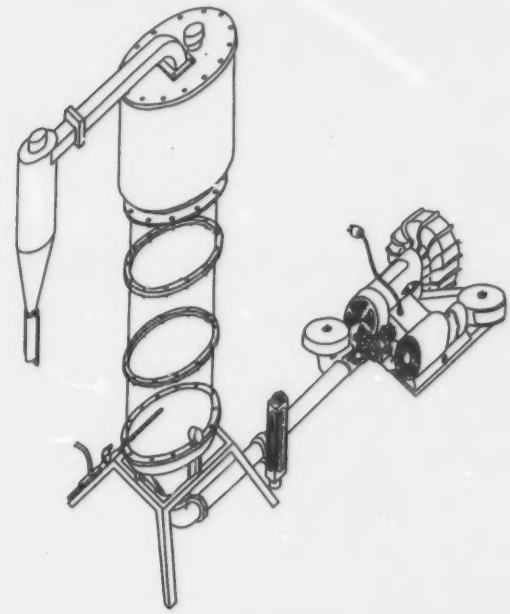

Figure 1. Experimental Apparatus

The flow rate of the fluidizing air was measured using a FLT-type "Flow Cell Bypass Flowmeter". This flowmeter is accurate to 2.5 percent of full scale and can be used up to maximum temperature and pressure of 60°C and 1035 kPa (150 psi), respectively. Three flow meters, with different ranges 2.4-11.8, 5.6-25.5 and 11.8-52.1 L/s (5-25, 12-54 and 25-1100 SCFM), were used depending on the required air flow rate. Each flowmeter was installed in a horizontal pipe having the same flowmeter size rating. The length of the pipe sections, downstream and upstream the flowmeter, were greater than three and eight times the diameter of the pipe, respectively.

Fluidized Bed Reactor

The fluidized bed reactor consists of: (a) a support stand, (b) a conical inlet section, (c) a distributor plate (d) a fluidizing column, (e) a disengagement section and (f) an outlet duct.

The support stand was constructed of 38 mm mild steel angle iron. A horizontal square structure made of four 380 mm long angle iron arc welded together was supported by four 475 mm long legs. The legs were arc welded to the corners of the square structure and were inclined at 15° to vertical for stability. The total height of the support stand was 460 mm. A 6 mm thick L-shaped, steel extension was welded at the middle of each side of the square structure in the vertical position so that the flange of the conical inlet

section of the fluidized bed reactor could lay on these extensions. Five 8 mm x 30 mm bolts and hex nuts were used to fix the inlet section to the support stand.

The vertical section of the air line was connected to a conical (funnel) inlet section made of 3.2 mm thick stainless steel material. The height of the conical section was 120 mm. Its sides were inclined at 45° to vertical. The bottom and top diameters of the concical section were 63 mm and 255 mm, respectively. A flange made of 8 mm thick stainless steel was welded to the upper portion of the funnel. The inner and outer diameters of the flange were 255 mm and 355 mm, respectively. A thick rubber gasket of 3 mm thickness was used between the flanges of the conical inlet section and the distributor plate to provide good sealing.

The distributor plate was made of 8 mm thick circular steel plate of 355 mm diameter. A circular area of 220 mm diameter was perforated. The total open area of the holes was 1.63 percent of the bed cross-sectional area. A total of 267 holes of 2 mm diameter each were drilled in the circular plate in the form of rings, starting from the centre with a pitch of 11.1 mm. To prevent falling of the sand through the holes of the distributor plate, a circular screen of 100 mesh size was point welded to the surface of the distributor plate. To test the effect of different types of distributor plates on the mixing characteristics of the fluidized bed, five plates having exactly the same open area were used. These were 10° concave, 5° concave, flat, 5° convex and 10° convex.

The main body of the fluidized bed (fluidizing column) was made of a plexi-glass cylinder having 255 mm inside diameter and 5 mm thickness. It was constructed in three pieces having lengths of 127.5, 255.0, 382.5 mm (0.5, 1.0, 1.5 D), respectively. This provided a maximum height of 765 mm. Two flanges made of 8 mm thick circular plates were glued to the top and bottom of each cylinder. The height of the fluidizing column was varied by fitting different sections of varying lengths. The sections were bolted to each other and rubber type O-rings of 3 mm thickness were used between the flanges to provide good sealing. Near the bottom of the bed, a drainage port of 55 mm diameter was used to remove the bed material when required. A mechanical injector (Figure 2) was mounted at the bottom part of the fluidized bed. In order to avoid the sand from flowing through the mechanical injector, an air line (with a pressure level just above that of the bed where the styrofoam balls were to be injected) was connected to the injector.

The entrainment of particles is dependent on the amount of space that is free above the bed known as the freeboard height. The gas bubbles erupt on the surface of the bed and splash solids far into the freeboard. To decrease the rate of

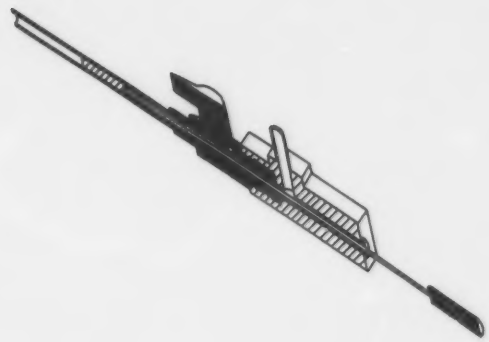

Figure 2. The Mechanical Injector

elutriation from the top of the fluidized bed, an enlarged section was used at the upper part of the bed. This part was made from 3.2 mm thick, hot rolled steel. The sides were inclined at 30° to vertical. The bottom and top diameters were 255 mm and 350 mm, respectively. The total height of this enlarged section, including the inclined part, was 395 mm. The top of the enlarged section was covered with 6 mm thick hot rolled steel, which was connected to the outlet duct.

The outlet duct was made of 1.6 mm thick stainless steel material. The vertical section of the duct was 100 mm in length whereas the horizontal was 400 mm in length. The vertical section of the duct had a cross-section of 85 mm x 85 mm at the bed exit whereas the horizontal section had a cross section of 80 mm x 40 mm at the cyclone inlet.

Cyclone

A cyclone connected to the outlet duct was used to capture the fine solid particles escaping from the top of the bed. The cyclone was made from 2 mm thick stainless steel metal sheet. It consisted of conical and cylindrical sections. The cylindrical section had a 150 mm diameter and a 300 mm height. The conical section had a 300 mm height and its sides were inclined at 10° to vertical. A gas outlet pipe of 75 mm diameter was extended 90 mm axially into the cyclone. At the bottom of the cyclone, the fine dust particles were collected in a cylindrical plexi-glass dust collector of a 60 mm diameter and a 200 mm height.

Pressure Drop Measurement System

The pressure drop was measured at different heights of fluidized bed using U-tube manometers (Figure 3). The first, second, third and fourth measurement points were 50, 350, 600 and 720 mm above the distributor plate, respectively. The fifth measurement point was on the outlet duct, connecting the bed exit to the cyclone. All these pressure measurements were done with respect to a

reference point located at the conical inlet section, 50 mm below the distributor plate. The five U-tube manometers were mounted on a vertical board. Colored water was used as the manometer liquid. Each measurement point was connected to a different U-tube using flexible plastic tubing of 10 mm diameter. The other end of the U-tube was connected to the reference point through a manifold. The pressure drop was measured in cm H_2O (gauge).

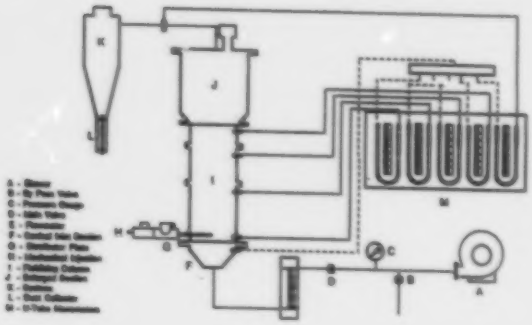

Figure 3. The Pressure Drop Measurement System

EXPERIMENTAL DESIGN

In this study, the effects of 5 parameters on the particle residence time and mixing pattern were investigated. These were (a) sand mean particle size, with two levels (b) bed height, with 4 levels, (c) fluidizing velocity, with 5 levels, (d) angle of distributor plate, with 5 different plates, and (e) the distance from the reactor central axis, with two levels. The experimental parameter are shown in Table 1. Six measurements were taken during each experimental run. This resulted in 400 experimental runs and 2400 measurements.

Selection of Styrofoam Balls

Five samples of styrofoam balls (each sample containing 400 balls of same diameter) were weighed. The volumes of the styrofoam balls were calculated from the diameters and the average density of each sample was estimated. Five samples of chopped straw (each containing 400 pieces of different sizes) were weighed. The volume of a styrofoam ball equivalent to that of straw was found by dividing the average weight of the straw by the average density of the styrofoam balls. From the equivalent volume, the diameter of the styrofoam balls equivalent to straw was calculated.

Table 1. Experimental Parameters

1. Sand Particle Size (PS)

	Fine	Coarse
dp	198	536
ρ_p	2600	2600
U_{mf}	4.2	26

2. Distributor Plate (DP)

Plate angle: 5° concave, 10° concave, flat, 10° convex, 15° convex

3. Bed Height (BH)

Packed bed height, H = 0.5 D, 1.0 D, 1.5 D, 2.0 D

4. Fluidizing Velocity (FV)

U_o = 1.00 U_{mf}, 1.25 U_{mf}, 1.50 U_{mf}, 1.75 Umf, 2.00 U_{mf}

5. Injection Distance (X)

X = 0.5 R, 1.0 R

dp = particle mean diameter (μm)
ρ_p = particle density (kg/m^3)
U_{mf} = minimum fluidizing velocity (cm/s)
U_o = fluidizing velocity (cm/s)
D = bed diameter (25.50 cm)
R = bed radius (12.75 cm)

EXPERIMENTAL PROCEDURE

Sand Particle Size Distribution

The most common method used to measure the size of irregular particles larger than 75 μm is sieving (Geldart, 1986). Sieving operation was performed for both types of the sand used in the experiments. After sieving the mean size of the particles was determined using equation 1.

$$\bar{d}_p = \frac{1}{\Sigma x_i/d_{pi}} \qquad (1)$$

where:

x_i = weight fraction of powder of size d_{pi} (%)

d_{pi} = mean sieve size of powder (um)

The particle size distributions of the fine and coarse sands are given in Table 2.

Experimental Protocol

For a given treatment combination, the selected distributor plate was fixed in place and the fluidizing column was assembled. The sand was then added to the reactor up to the required bed height. The blower was turned on and the flow rate was adjusted until the required fluidizing

velocity was obtained. The pressure differences measured at various points above the distributor plate were recorded.

Table 2. Sand Particle Size

Sieve aperture (μm) min.	max.	d_{pi} (μm)	Weight (%) Fine	Coarse
850	1410	1130.0	0.0	0.77
595	850	722.5	1.28	34.50
425	595	510.0	19.95	57.40
297	425	361.0	23.36	5.85
212	297	254.5	22.57	0.82
0	212	106.0	32.84	0.66

dp = mean particle size (μm)
dpi = mean sieve sie (μm)
dp for fine sand = 198 μm
dp for coarse = 536 μm

The mechanical injector used to inject the styrofoam balls was adjusted to the center of the reactor. The injector was then used to inject the styrofoam balls at the center of the bed and the time required for the ball to travel from the bottom of the bed to the surface was measured using a stop watch. This was repeated six times using various colored styrofoam balls. The tip of the mechanical injector was then positioned half way between the reactor wall and the center. The procedure was then repeated until six measurements were obtained.

RESULTS AND DISCUSSION

The effects of sand particle size, bed height, fluidizing velocity and distributor type on the mixing patterns and particle residence time were investigated. The residence time was measured at the center of the bed and at a radial distance from the wall equal to one half the radius. High speed photography was used during the experimental runs in order to gain a better understanding of the mixing and fluidization processes. The films were analyzed on a photo optical analyzer. This unit allowed frame by frame observation of the films and consequently gave a good picture of the sand and air bubble movement.

The experiments were carried out at room temperature. The flowmeters were calibrated at 20^0 C and 1 atm. pressure. However, if the air flowing through the meter was at a different temperature and/or pressure, the actual flow rate was calculated from the following equation 2.

$$F = G\sqrt{\frac{P_1 T_1}{P_0 T_0}} \qquad (2)$$

where:

- F = actual flow rate (cm^3/s)
- G = gauge flow rate reading (cm^3/s)
- T_0 = absolute temperature of air for which the gauge is calibrated (°K)
- T_1 = absolute temperature of air flowing through meter (°K)
- P_0 = absolute pressure of air for which the gauge is calibrated (KPa)
- P_1 = absolute pressure of air flowing through meter (KPa)

When the styrofoam balls were injected from the bottom of the fluidized bed, they moved upward in the bed to the surface because their density is much smaller than that of the sand. As six measurements were taken during each experimental run, a total of 2400 measurements should have been collected. However, with low bed heights (HH = 0.5 - 1.0 D) and high fluidizing velocities (U = 1.75 - 2.00 U_{mf}), it was not possible to measure the residence time with the technique used in this study. Bigger bubbles were size was observed which erupted at the surface making it difficult to see the styrofoam balls at the time when they reach the surface. On the other hand with high bed heights (HH = 1.5 - 2.0 D) and low fluidizing velocities (U = 1.00 - 1.25 U_{mf}), it was not possible for the styrofoam balls to reach the sand surface as fluidization was not achieved. As a result, statistical analysis of the whole experimental result was not possible due to the missing measurements. It was, therefore, decided to eliminate 3 levels of fluidizing velocity and analysis of variance performed on 960 measurements as shown in Table 3. The effects of all the variables (sand particle size, bed height, type of distributor plate and fluidizing velocity) were highly significant (at 0.0001). However, there was no significant differences between the measurements taken at half the radial distance from the central axis and those taken at the center of the bed. The analysis also showed that the interactions between the various variable were highly significant (at 0.0001).

The results show that greater values of residence time were obtained with the larger sand particle size. This is due to the difference in bubble velocities caused by different groups of particles. According to Geldart's classification (1986), fine sand (dp = 198 μm) falls within the range of Group-B particles (60 μm < dp < 500 μm) and coarse sand (dp = 536 μm) falls on the boundary between Group-B and Group-D) particles. With Group-B particles most bubbles rise more quickly than the interstitial gas velocity whereas with Group-D particles all but the largest bubbles rise more slowly than the instertitial gas velocity.

The pressure drop across the distributor plate (ΔP_d) is taken to be 10 percent of the pressure drop across the bed (ΔP_b). The pressure drop across the bed (ΔP_b) was determined from the following equation:

Table 3. Analysis of Variance

SOURCE	DF	SS	MS	F	PR > F
TOTAL	959	3332.47			
MODEL	159	2141.24	13.47	56.34	0.0000
PS	1	58.09	58.09	243.00	0.0000
DP	4	210.78	52.70	220.44	0.0000
BH	3	1306.55	435.52	1821.96	0.0000
FV	1	87.89	87.89	367.70	0.0000
X	1	0.02	0.02	0.07	0.7867
PS*DP	4	91.47	32.87	95.66	0.0000
PS*BH	3	25.38	8.46	35.39	0.0001
PS*FV	1	9.20	9.20	38.49	0.0001
PS*X	1	1.05	1.05	4.41	0.0361
DP*BH	12	66.12	5.51	23.05	0.0000
DP*FV	4	9.82	2.46	10.27	0.0001
DP*X	4	4.85	1.21	5.07	0.0005
BH*FV	3	43.42	14.47	60.55	0.0001
BH*X	3	5.39	1.80	7.52	0.0001
FV*X	1	0.67	0.67	2.82	0.0937
PS*DP*BH	12	123.23	10.27	42.96	0.0000
PS*DP*FV	4	2.95	0.74	3.09	0.0154
PS*DP*X	4	1.50	1.50	1.57	0.1805
PS*BH*FV	3	13.06	4.35	18.21	0.0001
PS*BH*X	3	0.22	0.07	0.30	0.8243
PS*FV*X	1	0.0004	0.0004	0.00	0.9663
DP*BH*FV	12	15.56	1.30	5.43	0.0001
DP*BH*X	12	9.84	0.82	3.43	0.0001
BH*FV*X	3	5.34	1.78	7.46	0.0001
PS*DP*BH*FV	12	27.58	2.30	9.62	0.0001
PS*DP*BH*X	12	7.19	0.60	2.51	0.0031
PS*BH*FV*X	3	1.24	0.41	1.73	0.1585
DP*BH*FV*X	16	6.61	0.41	1.73	0.0369
PS*DP*BH*FV*X	16	6.20	0.39	1.62	0.0579

$R^2 = 0.92$
CV = 12.32 %
PS = particle size
DP = distributor plate
BH = bed height
FV = fludization velocity
X = radial distance from wall

$$\Delta P_b = L_{mf} (1 - \varepsilon_{mf}) (\rho_s - \rho_g) \qquad (3)$$

where:

L_{mf} = The bed height (cm)
ε_{mf} = The voidage value at the minimum fluidization condition
ρ_s = The density of the solid particles (g/cm^3)
ρ_g = The density of the fluidizing gas (g/cm^3)

Reynolds number for the total flow approaching the plate was calculated and the corresponding value for the orifice coefficient (C_d) was selected from figure-12 in Kunii (1977). The velocity of fluid through the orifices (U_{or}) was determined from equation 4 (Kunii and Levenspiel, 1977):

$$U_{or} = C_d \sqrt{\frac{2 g_c \Delta P_d}{\rho_g}} \qquad (4)$$

The fraction of open area was found from the ratio U_{or}/U_o. Deciding on the orifice diameter (d_{or}), the corresponding number of orifices per unit area of distributor plate (N_{or}) was determined from equation 5.

$$U_o = \pi/4 (d_{or})^2 U_{or} N_{or} \qquad (5)$$

The results showed that increasing the angle of the convex or decreasing the angle of the concave increased the residence time. Thus, the minimum and maximum values for the residence time were obtained with plates having 10° concave and 10° convex, respectively. The bed height significantly affected the residence time. The increase in the bed height increased the residence time considerably.

In freely bubbling fluidized beds, vertical transport and vertical mixing of particles is achieved by the bubble motion (Rowe and Nienow, 1976; Hsiung and Grace, 1978; and Nienow and Rowe, 1981). Each bubble carries a wake of particles which is ultimately deposited on the bed surface. In addition, it causes a drift of particles to be drawn up as a spout below each bubble. Therefore, the styrofoam balls, were carried up in the bed by the bubbles and the residence time was primarily the function of bubble velocity and frequency. The mean values of the residence time decreased with the increase in fluidization velocity. Bubble velocity generally increases with the increase in both the bubble diameter and fluidization velocity. The bubble diameter, also increases when fluidization velocity was increased. Therefore, the increase in fluidizing velocity resulted in higher bubble velocities which consequently gave lower residence times.

Regression analysis was also performed on the data as shown in Table 4. The regression equation is as follows:

$$\begin{aligned} T = {} & 1.167284 - 0.00957\ PS - 078082\ DP + 0.05833\ PH \\ & - 0.71994\ FV + 0.00215\ PS*DP + 0.00058\ PS*BH \\ & + 0.00555\ PS*FV + 0.02223\ DP*BH + 0.41132\ DP*FV \\ & - 0.00008\ PS*DP*BH - 0.00115\ PS*DP*FV \\ & - 0.00032\ PS*BH*FV - 0.01147\ DP*BH*FV \\ & + 0.00004\ PS*DP*BH*FV \qquad (6) \end{aligned}$$

where:

T = residence time (s)
PS = sand particle size (μm)
BH = bed height (cm)
FV = fluidizing velocity (cm/s)
DP = distribute plate angle (°)

The regression analysis indicated that the range of fluidizing velocity used in these analyses was too narrow as the differences were smaller than the variation among the replicates as the coefficient of variability of the regression analysis was 28%. Although this may appear high, it is within the reporter values in the literature.

Table 4. Regression Analysis

Variable	DF	Coefficient	ST	T	PR > T
Intercept	1	1.16284	0.69904	1.663	0.0965
PS	1	-0.00957	0.00235	-4.072	0.0001
DP	1	-0.78082	0.23867	-3.273	0.0011
BH	1	0.05833	0.00371	15.735	0.0001
FV	1	-0.71994	0.42274	-1.703	0.0889
PS*DP	1	0.00215	0.00059	3.640	0.0003
PS*BH	1	0.00058	0.00005	11.476	0.0001
PS*FV	1	0.00555	0.00143	3.253	0.0012
DP*BH	1	0.02223	0.00684	3.873	0.0001
DP*FV	1	0.41132	0.14644	2.809	0.0051
PS*DP*BH	1	-0.00008	0.00002	-4.791	0.0001
PS*DP*FV	1	-0.00115	0.00036	-3.167	0.0016
PS*BH*FV	1	-0.00032	0.00003	-10.405	0.0001
DP*BH*FV	1	-0.01147	0.00419	-2.735	0.0064
PS*DP*BH*FV	1	0.00004	0.00001	3.830	0.0001

R = 0.81
CV = 28.69%
PS = particle size
DP = distributor plate
BH = bed height
FV = fluidization velocity

To improve the mixing properties of the binary mixture, which has great tendency for segregation, due to density differences, higher fluidization velocities should be used during the experiments. Since residence time is affected a lot by the degree of mixing, it will also be improved by increasing the fluidization velocity. Therefore further studies should be carried out using a better technique that will give more information about the mixing characteristics and residence time of the straw particles. It is necessary to perform the experiments at higher fluidization velocities (3-5 U_{mf}) which are also closer to the operating conditions of bubbling beds with better mixing properties.

CONCLUSIONS

The results indicated that particle size, bed height, fluidizing velocity and distributor plate have significant effects on the residence time. The position of injection did not have any significant effect on the residence time. The measurements were taken only for two positions of the injector, one at the center of the bed and the other halfway between the center and the wall of the bed. Thus two points were not enough to conclude the effect of the radial position on the residence time. However, it is obvious that particles descend in the bubble free regions so that overall convective circulation is set-up and rapid localized mixing results.

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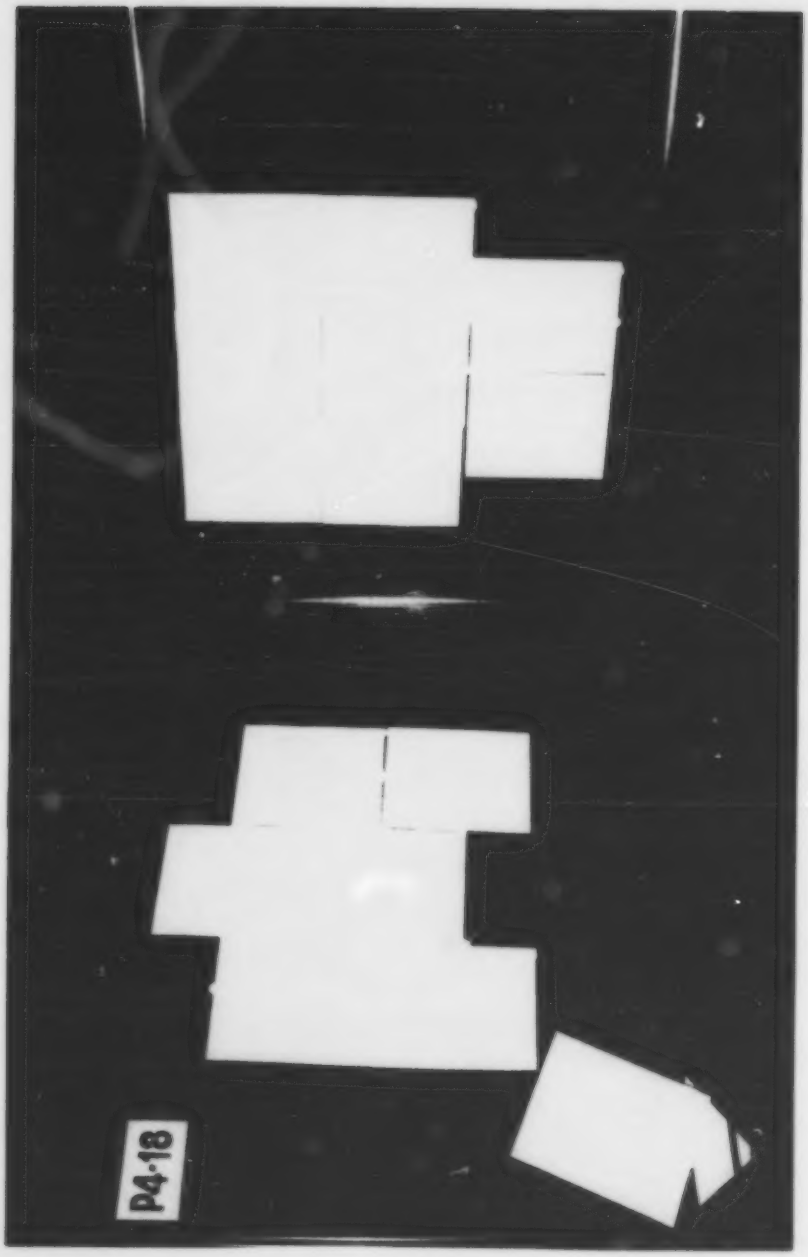
P4-18

THERMOGRAVIMETRIC CHARACTERISTICS OF CEREAL STRAWS

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Thermochemical conversion technologies such as pyrolysis, combustion and gasification use elevated temperatures to recover the energy content of biofuel materials. During the thermochemical conversion process, the thermal degradation of the various components of the organic fuel material occurs. Straws are one of the most commonly available lignocellulosic materials which can be converted to different types of fuels and chemical feedstocks through a variety of thermochemical conversion processes. Although, cellulose, one of the major constituents of straws, has been extensively investigated for its thermal behaviour, straw itself has not been given the same consideration. Full understanding of the biofuel properties and its thermochemical behaviour is very essential for the proper design of thermochemical conversion systems. The objective of this paper is to examine the thermogravimetric behaviour of four cereal straws (wheat, barley, oats and rye) at five heating rates (10, 20, 30, 40, 50° C/ minute) in air and controlled atmosphere. The results of the thermal degradation rate, initial degradation temperature and the residual weight at 600° C will be presented.

Les techniques de conversion thermochimique, comme la pyrolyse, la combustion et la gazeification, utilisent des temperatures elevees pour recuperer le contenu energetique des biocombustibles. Pendant la conversion thermochimique, il y a degradation thermique des divers constituants du combustible organique. La paille constitue l'une des matieres lignocellulosiques couramment disponibles qu'il est possible de transformer en differents types de combustibles et de charges d'alimentation a l'aide de divers procedes de conversion thermochimique. Le comportement thermique de la cellulose, l'un des principqux constituants de la paille, a ete etudie en profondeur, mais la paille n'a pas fait l'objet d'etudes aussi exhaustives. Il est tres important de connaitre parfaitement les proprietes du biocombustible et ses caracteristiques thermochimiques pour concevoir correctement des systemes de conversion thermochimique. L'objectif de cette communication est d'examiner le comportement thermogravimetrique de quatre pailles de cereale (ble, orge, avoine et seigle) a cinq taux de chauffage (10, 20, 30, 40 et 50°C/minute) dans l'air et dans une atmosphere controlee. On y presente la vitesse de degradation thermique, la temperature de degradation initiale et le poids des residus a 600°C.

INTRODUCTION

Cereal straws are one of the most commonly available lignocellulosic materials which can be converted to different types of fuels and chemical feedstocks through a variety of thermochemical conversion processes. Thermochemical conversion thechnologies such as combustion, gasification, and pyrolysis use elevated temperatures to convert the energy content of biofuel materials. During thermochemical conversion, the thermal degradation of the various components of the organic fuel materials occurs. Although, cellulose, one of the major constituents of straws, has been extensively investigated for its thermal behaviour, straw itself has not been given the same consideration (Lipska-Quinn et al., 1985).

Thermogravimetric analysis (TGA) is one of the major thermal analysis techniques used to study the thermal behaviour of carbonaceous materials. The rate of weight loss of the sample as a function of temperature and time is measured to predict thermal behaviour of the material. TGA provides a semiquantitative understanding of thermal degradation processes occurring during thermochemical conversion (Milne, 1981). Shafizadeh and DeGroot (1976) reported that the chemical composition, heating rate, ambient atmosphere, temperature and inorganic substances are the major factors that affect the thermal behaviour of biomass.

Cellulose, hemicellulose and lignin are the major components of straw (Table 1). Different components of straw exhibit different thermal

behaviour with hemicellulose being the least stable component of straw. Shafizadeh (1968) reported that cellulose and hemicellulose components of biomass breakdown at temperatures above 300°C producing tarry products and relatively small amounts of pyrolyzates. However, the overall thermal behaviour of the aggregate reflects the sum total of thermal behaviours of its components.

Table 1. Chemical Composition of Straw (Theander and Aman, 1978)

Crop	Chemical Composition (% on dry weight basis)		
	Cellulose	Hemicellulose	Klason Lignin
Barley	29	25	22
Oats	30	22	23
Wheat	27	21	21
Rye	37	23	20

Thermal decomposition of biomaterials could take place in both anaerobic conditions (steam, hydrogen, self generated gas) and aerobic conditions (air, oxygen). Pyrolytic reactions cause incomplete thermal degradation of carbonaceous materials resulting in char, condensible liquids or tars and gaseous products, generally under anaerobic conditions (Soltes and Elder, 1969). Gasification reactions occur as a combination of pyrolytic reactions followed by higher temperature reactions of char, tars and primary gases to yield mainly low molecular weight gaseous products (Milne, 1981). Shafizadeh and DeGroot (1976) and Lipska-Quinn et al. (1985) reported a higher rate of thermal decomposition by oxidation of the substance at lower temperatures in presence of air (or oxygen) than in the absence of air (or oxygen).

The presence of inorganic materials either as additives or natural ash content strongly affects the thermal behaviour of the cellulosic materials. The influence of the inorganic materials has been investigated primarily in relation to the problems of flame proofing, and fire prevention (MacKay, 1968; and Broido, 1966). It has also been studied in connection with thermochemical conversion of biomass to fuel and chemicals (Shafizadeh and DeGroot 1976). The catalytic effect of the inorganic materials is particularly pronounced with alkaline compounds and acidic reagents. Shafizadeh and DeGroot (1976) studied the suppressive effect of diammonium phosphate, $(NH_4)_2PO_4$, on thermal behaviour of cellulose. Lowering of the pyrolysis and increased char formation were observed. The natural impurities and ash content could also produce profound effects. Straws from different cereal crops have widely varying ash contents and ash composition. Thus, the thermal analysis methods could indicate the effects of different straw compositions, ash contents and ash compositions on lowering of the decompostion temperatures, the relative amounts of char and volatiles formed, the related heat of evaporation and the heat of combustion of gaseous products.

OBJECTIVES

The aim of the study was to examine the thermogravimetric behaviour of straws obtained from four cereal crops as related to thermochemical conversion processes. The specific objectives of the study were:

(a) to conduct thermogravimetric analysis on four cereal straws (wheat, barley, oats and rye) at three heating rates (10, 20 and 50° C/min) in two atmospheres (air and nitrogen)

(b) to determine the thermal degradation rate, active and passive pyrolysis zones, initial degradation temperature and the residual weight at 600° C.

EXPERIMENTAL PROCEDURE

Straw Collection

Four major cereal crops were selected for the thermogravimetric analysis. These were: wheat, barley, oats and rye. The most commonly grown variety of each crop was selected for the study. The selected varieties were: Max, Kadeth, Sentinel and Kustro for wheat, barley, oats and rye respectively. Straw samples were obtained from harvested fields in the Annapolis Valley, Nova Scotia. Samples of approximately 5.0 kg of straw were collected from each field, placed in polyethylene bags and transported to the Thermal Analysis Laboratory at the Technical University of Nova Scotia in Halifax. The straws were dried on the same day to avoid further deterioration due to higher moisture content. The dried straws were then stored in polethylene bags for future processing.

Sample Preparation

Dried straw samples of 1kg each were first coarse ground through a 20 mesh sieve on a medium size Wiley Mill. The coarse ground materials were then reground through a 40 mesh seive on the Wiley Mill. The samples were dried at 105° C for 24 hours in a forced air drying oven. These were stored in air tight plastic containers until they were needed for the thermogravimetric analysis.

Thermal Analysis

Straw samples were subjected to thermogravimetric analysis in dry air atmosphere at three different heating rates. The heating rates used were: 10°C/min, 20°C/min and 50°C/min. Samples weighing between 80 to 90 mg were heated at preselected heating rates from ambient to 700°C in NETZSCH Simultaneous Thermal Analyzer (STA 409). The continuous record of weight loss and temperature was obtained. The data was analyzed to determine thermogravimetric analysis indices: thermal degradation in active and passive zones, initial degradation temperature and residual weight at 600°C.

RESULTS AND DISCUSSION

The results of thermogravimetric analysis (TGA) are presented in Table 2. Thermogravimetric characteristics of the straw samples at different heating rates are shown as thermograms on Figures 1-7. Figures 1-3 show the effect of crop on the thermogravimetric behaviour of straw at 10, 20 and 50° C heating rates; whereas the effects of heating rates on thermogravimetric characteristics of wheat, barley, oats and rye are shown in Figures 4-7.

Table 2. Thermogravimetric Analysis of Straw

Straw	Heating Rate (°C/min)	TDR (%/min) Active zone	TDR (%/min) Passive zone	IDT (°C)	RW (%)
Wheat	10	3.34	1.05	172	12.49
	20	5.84	1.40	147	23.46
	50	11.86	2.58	80	22.60
Barley	10	4.6	1.05	196	17.65
	20	7.48	1.53	196	27.36
	50	14.12	1.80	137	29.82
Oats	10	4.39	1.05	208	14.07
	20	7.27	1.15	174	22.98
	50	12.54	1.83	147	27.56
Rye	10	5.52	1.09	231	14.16
	20	7.96	1.94	193	18.83
	50	16.71	1.62	172	21.81

TDR = thermal degradation rate
IDT = initial degradation temperture
RW = residual weight at 600°C

Thermal Degradation Rate

During thermal degradation of straw samples, two distinct pyrolysis zones were observed. Once the threshold temperature for thermal decomposition of the sample material was reached, there was a sharp drop in the weight of the samples up to a certain temperature. This was termed as active pyrolysis zone. Thereafter, the rate of weight loss decreased till it became zero. However, the present study was restricted to maximum final temperature of 700°C. Thus, the passive pyrolysis zone was the one in which there was decreasing rate of weight loss with respect to temperature. These two zones are quite evident in all thermograms shown in Figures 1-7.

The thermal degradation rate, both in active and passive pyrolysis zones, increased with increases in heating rate. The proportional increase of thermal degradation rate with increases in heating rate was more in active pyrolysis zone than in passive pyrolysis zone for all samples. Thermal degradation was largest at all heating rates for rye straw and lowest at all heating rates for wheat straw. This indicated

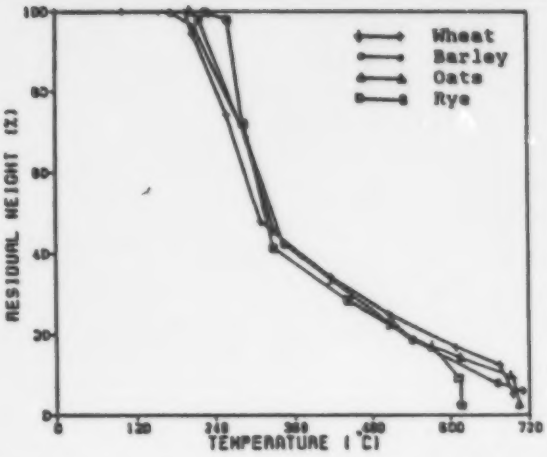

Figure 1. Straw thermograms at 10°C/min.

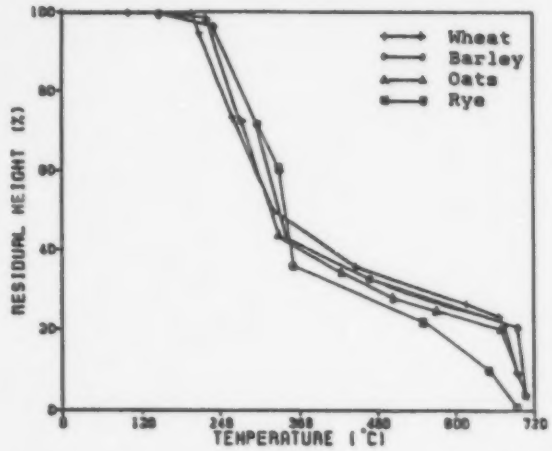

Figure 2. Straw thermograms at 20°C/min.

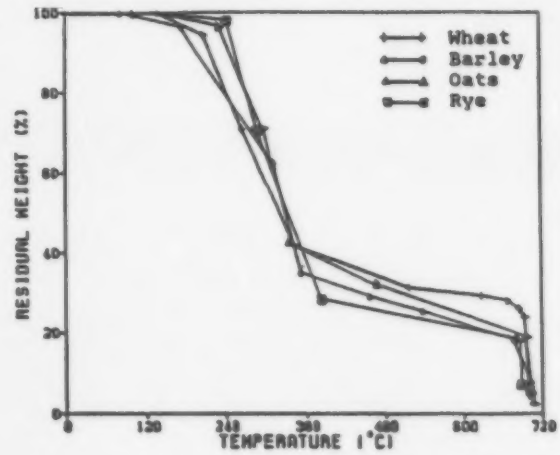

Figure 3. Straw thermograms at 50°C/min.

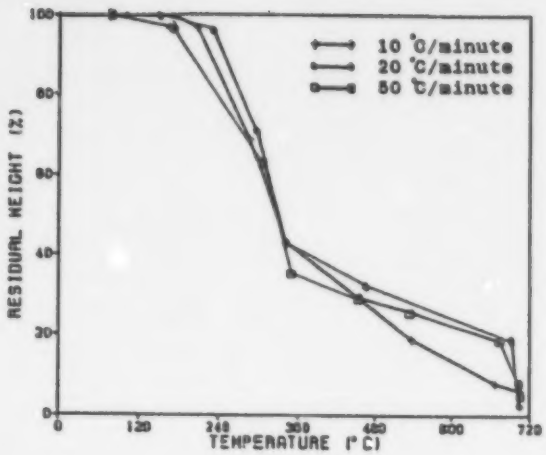

Figure 4. Wheat straw thermograms at various heating rates

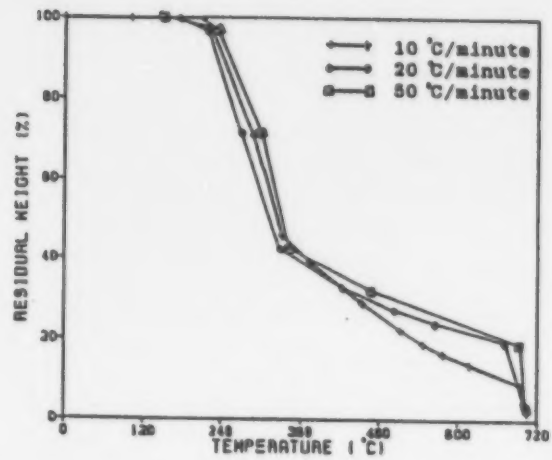

Figure 6. Oats straw thermograms at various heating rates

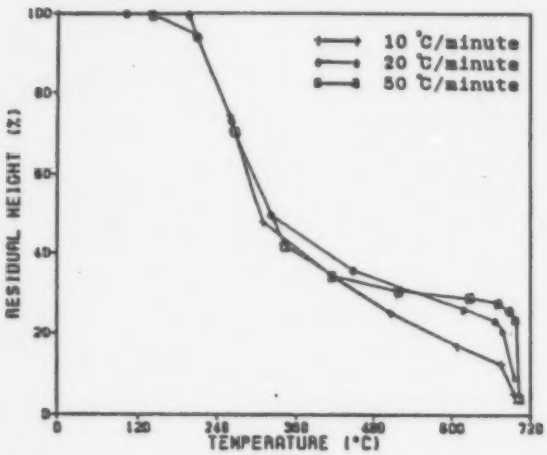

Figure 5. Barley straw thermograms at various heating rates

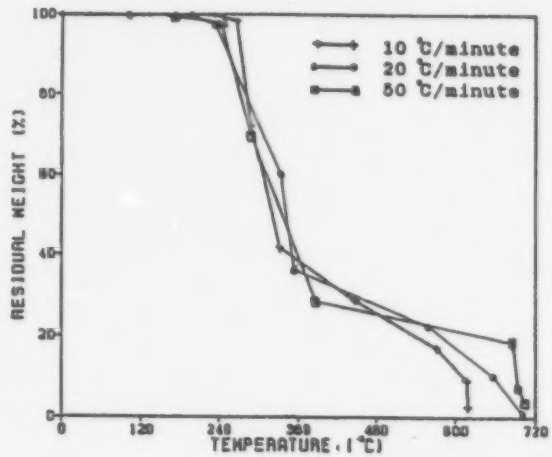

Figure 7. Rye straw thermograms at various heating rates

that rye straw is more easily thermochemically degradable than wheat straw. In terms of their thermal degradability next to rye straw was barley straw, followed by oats straw and then wheat straw.

The thermal degradability is affected by the chemical composition of straw as different components of lignocellulosic materials have different thermal behaviour. Higher thermal degradation rate of rye straw might be due to larger percentage of cellulose and hemicellulose components in comparison to those of wheat, barley and oats as reported by Theander and Aman (1978). Larger percentages of volatile matter and low ash contents of rye straw as compared to those of wheat straw might have also contributed the higher termal degradability of rye straw. These results are in close agreement with those reported by Lipska-Quinn et al. (1985) for rice straw.

Thermochemical degradation of the biofuel materials depends upon the rate and extent of the pyrolytic reactions and the sequence of these reactions. Pyrolytic reactions, in turn, depend upon the duration and intensity of heating of the substrate. Thus, different heating rates produce different end products. Shafizadeh and DeGroot (1976) reported that long heating periods allow the sequence of consecutive reactions to take

place. On the contrary, the flash pyrolysis could reduce the secondary reactions and disallow the further degradation of the products. Lipska-Quinn et al. (1985) studied thermal decomposition of rice straw at different heating rates. They found that the rate of degradation in the active pyrolysis zone markedly increased with the increase in heating rate. A significant decrease in the temperature of initial degradation was also observed when the heating rate was increased.

Initial Degradation Temperature

The temperature at which the degradation start is termed initial degradation temperature. At lower temperatures wheat straw exhibited different thermal degradation than those of other straw samples. The initial degradation temperature for rye straw, which apparently had highest thermal degradation rate, was highest among the different straws at all heating degradation rates. With increases in heating rate, the initial degradation temperature decreased for all straw samples. Wheat straw sample started degrading at 80° C while heated at 50° C/minute whereas at 10° C minute heating rate, its initial degradation temperature was 172° C. Rye straw started degrading at 231°C, 193°C and 172°C when heated at 10°C/minute, 20°C/minute and 50°C/minute respectively.

Lipska-Quinn et al. (1985) observed marked decrease in initial degradation temperature for rice straw and its components while increasing heating rate. Hemicellulose and lignin components of lignocellulosic material start degrading at lower temperatures than cellulose. Their rate of thermal degradation is lower than that of cellulose as observed by Shafizadeh and McGinnis (1970). Thus higher percentage of cellulose in rye straw than that in wheat straw as reported by Theander and Aman (1978) might have caused the higher initial degradation temperature for rye that wheat barley and oats straw.

Residual Weight at 600°C

Shafizadeh and DeGroo (1976) reported that three major constituents of ligno-cellulosic materials (hemicellulose, cellulose and lognin) are chemically reactive and decompose thermochemically between temperature range of 150-500°C (hemicellulose occurs at 150-350°C, cellulose occurs at 275-350°C and Lignin occurs at 250-500°C). Thus, a temperature level higher than 500°C (i.e. 600°C) was selected to compare the residual weights of different straw samples under study.

Barley straw exhibited the largest weight at 600°C in comparison to the other three straws. This might be due to larger ash content of barley straw than that of other straws. Residual weight increased with increase in heating rate with all samples. Lipska-Quinn et al. (1985) also observed increases in residual weight with increase in heating rate during the thermal degradation of rice straw. This indicated that sufficient time was not available for the consecutive pyrolytic reactions to occur at higher heating rates. Thus larger percentages of samples were left unconverted at higher heating rates.

The desired temperatue range for processing biomass is below 500° C . However, the industrial processes for biomass gasification and liquefaction are usually designed for temperatures above 600° C . The higher temperatures are required to convert the char at appreciable conversion rates through heterogenous reactions with gaseous components such as water, carbon dioxide and oxygen. Shafizadeh and DeGroot (1976) reported that at higher temperatures, presence of water and steam speeds up the breakdown and degradation of the molecules by hydrloysis of the substrate and rearrangement of intermediate products. The steam plays a more important and direct role as a reactant in the gasification of char and related processes. At higher temperatures carbon dioxide and hydrogen also act as reactants. In the presence of air or oxygen, at higher temperature, the oxidation of the volatile pyrolysis products results in flaming combustion. This further enhances the oxidation of char.

SUMMARY AND CONCLUSIONS

Thermogravimetric analysis of four common cereal straws namely wheat, barley, oats and rye were conducted. The straw samples were heated in air atmosphere at 10°C/minute, 20°C/minute and 50°C/minute. The rate of weight loss with respect to temperature and time was determined.

Thermograms for different straws depicting plot of residual weight as percentage of original weight of sample versus temperature were obtained. Data was analyzed to determine the initial degradation temperature, the rate of thermal degradation in active as well as passive pyrolysis zones, and the residual weight at 600°C.

During thermal decomposition of straw, the thermal degradation rate increased as the heating rate was increased. The higher the cellulosic content of the straw, the higher is its thermal degradation rate. Rye straw has higher thermal degradation rate than those of wheat, barley and oats mainly due to higher cellulosic content. Initial degradation temperature of straw decreased as the heating rate was increased. The lower the cellulosic content of the straw, the lower is its initial degradation temperature. Wheat straw has the lowest initial degradation temperature among the four straws under study, mainly because of lower cellulosic content. Residual weight at 600°C increased as the heating rate was increased, indicating incomplete conversion due to insufficient time period for pyrolytic reactions to take place. The higher the ash content of the straw, the larger is the residual weight. Barley straw has higher residual weight (at 600°C) than other straw because of its higher ash content. Rye straw is highly degradable through

thermochemical conversion process in comparison to wheat straw, barley straw and oats straw.

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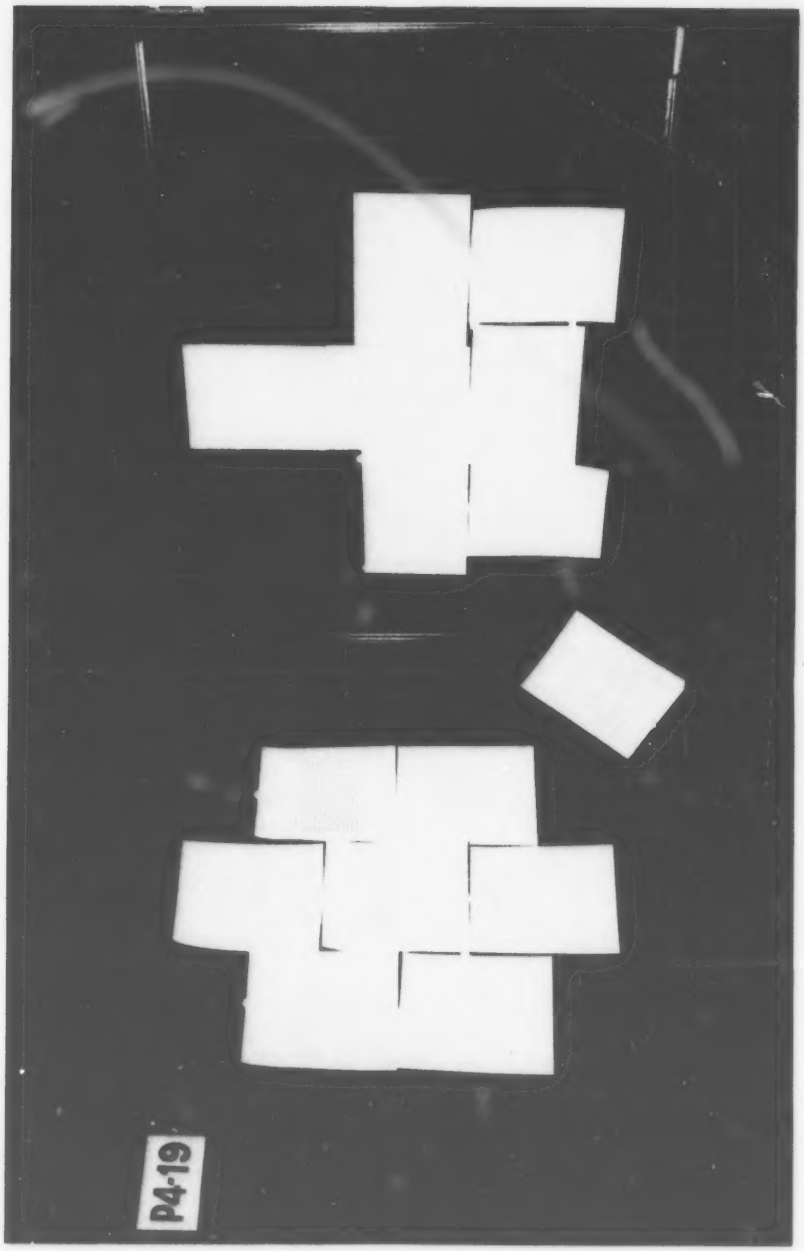
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PHYSICAL AND CHEMICAL PROPERTIES OF CEREAL STRAW AS RELATED TO THERMOCHEMICAL CONVERSION

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Cereal straws are residues of cereal crops such as wheat, oats, rye, barley and rice. These represent a major portion of the 2,000 million tonnes world annual production of agricultural crop residues. The production of cereal straws is quite well distributed geographically over differnt parts of the world. Large quantities of straws are considered surplus which can be made available for use as a source of energy in many countries. The current intensive cultivation practices of cereal crops coupled with increased productivity have increased the amount of surplus straw in many parts of the world creating serious disposal problems. Attempts have been made to develop suitable systems such as combusters and gasifiers for the recovery of energy from straw. These were met with limited success due to the lack of information on the straw properties pertaining to designing thermochemical conversion system. Full understanding of the physical (moisture content, bulk density, particle size and particle size distribution) and chemical (ash composition, and ash fusibility characteristics) properties of the straw is very essential for proper design of such systems.

La paille de cereale le residu de cultures cerealieres comme le ble, l'avoine, le seigle, l'orge et le le riz. Cette paille constitue une part importante des 2000 millions de tonnes de residues de cultures agricoles produits chaque annee a l'echelle mondiale. La production de paille de cereale est tres bien distribuee geographiquement dans differentes parties du monde. De grandes quantites de paille, qui sont considerees excedentaires, pourraient servir a produire de l'energie dans de nombreux pays. Les methodes de culture intensive actuellement utilisees pour produire des cereles et la productivite accrue ont donne lieu, dans plusieurs regions du monde, a des surplus de paille dont l'elimination constitue un grave probleme. A plusieurs reprises, on a tente de mettre au point des systemes, comme des systemes de combustion et de gazeification, pour recuperer l'energie que renferme la paille. Ces tentatives n'ont eu qu'un succes limite, car on ne posse dait pas suffisamment de donnees sur les proprietes de la paille don il faudrait tenir compte lors de la conception de systemes de conversion thermochimique.

OBJECTIVES

The aim of this paper is to discuss the various aspects of physical and chemical properties of straw as related to thermochemical conversion processes. These include moisture content, bulk density, particle size, heating value, proximate analysis, ultimate analysis and ash analysis.

STRAW COLLECTION AND SAMPLE PREPARATION

Straw Collection

Four major cereal crops were selected for physical and chemical analyses. These were: wheat, barely, oats and rye. In order to study the varietal differences within a given crop, samples from four commonly grown varieties of wheat (Absolvant, Max, Monopol and Vuka), three varieties of barley (Kadeth, Leger and Laurier), three varieties of oats (Sentinel, Shaw and Tibor) and two varieties of rye (Kustro and Danko) were collected for the study. Straw samples were obtained from harvested fields at six different farm locations in the Annapolis Valley, Nova Scotia. Small rectangular bales (850 mm x 500 m x 350 mm) as well as loose straw samples of approximately 15.0 kg each were brought to the Gasification Laboratory at the Technical University of Nova Scotia in Halifax.

Sample Preparation

Dried straw samples were coarse ground through a 20 mesh sieve on a medium size Wiley Mill. Approximately 1.0 kg of material from each crop variety was ground so that a sufficient quantity of material would be available for ash analyses. Portions of the coarse ground samples were reground through a 40 mesh seive on the Wiley Mill. Fine ground samples were used for proximate analyses, ultimate and heat value analyses. All samples were dried at 105°C for 24 hours in a

forced air drying oven. After oven drying, the samples were stored in air tight plastic containers till needed.

Ash Preparation

The ash samples were obtained by ashing the coarse ground straw in porcelain crucibles using muffle furnace at 600°C for one hour at first. The ash samples were allowed to cool down in a dessicator and weighed after cooling. The ashing was again performed for one hour. The samples were allowed to cool down again in a dessicator and then weighed. The process was repeated until there was no weight change in ash sample. The ash was stored in air tight plastic containers until the ash analyses were performed.

PHYSICAL PROPERTIES MEASUREMENTS

Moisture Control

Moisture content tests were performed on the loose straw sample collected from the field during harvesting. Straw samples weighing approximately 1 kg each were placed in large aluminum dishes. The dishes were placed in an air forced oven and the straw was dried at 105°C until a constant weight was acheived. The moisture content of the straw of the various crops was then calculated on wet basis.

Bulk Density

Only small bales of straws of various cereal crops were collected from the field. The bulk density of the bales was determined using 10 bales of each variety. The dimensions of the bale (depth, width and height) were calculated. The bale was then weighed and the bulk density was determined.

Particle Size Distribution

A straw chopping system was used to chop the straw into particles small enough for feeding the gasifier using an auger system especially designed for this purpose. Samples of the chopped straw were collected randomly for sieve analysis to determine the size distribution of straw particles. An electrical sieve shaker (Hoskin Scientific Limited) driven by a 0.25 hp electric motor running at 1725 rpm was used. The shaker contained six standard sieves and a bottom pan whose specifications are given in Table 1. The system of sieves was placed onto the electrically operated sieve shaker. A sample of the chopped straw was weighed and put into sieve No. 1 which was then covered with the sieve lid. The shaker was operated for 30 minutes. The chopped straws, collected in each sieve, were then analysed for weight, length and width distribution.

Table 1. Sieve Characteristics

Sieve Number	Mesh Number	Opening Size (mm)
1	4	4.7600
2	8	2.3800
3	14	1.4100
4	30	0.5950
5	50	0.2990
6	100	0.1490
pan		0.0000

THERMOCHEMICAL ANALYSES

Heating Values

A bomb calorimeter (Parr Model 1241 Automatic Adiabatic Calorimeter) was used to determine the higher heating value of the straw samples. The procedure used closely followed the procedure given in the ASTM Standard Test Method for Gross Calorific Values of Coal and Coke by the Adiabatic Bomb Calorimeter (D-2015-85). The bomb calorimeter measures the heat released by combustion of fuel with oxygen. This is referred to as the constant volume higher heating value. Difficulties were experienced while burning samples of straw in the bomb calorimeter. The sudden release of volatiles expelled the straw particles from the combustion crucibles, resulting in incomplete combustion. To avoid these problems, the ground samples were formed into 0.5-1.0 g pellets. This was achieved by compressing the known amount of the ground straw in a moulding die by a hydraulic press to a pressure of 50 MPa at which the pellets retained their shape on release of pressure. No additive was used while making pellets.

Proximate analysis

The proximate analysis was performed on the ground-oven dried straw samples to determine the weight fractions of volatiles, ash, and fixed carbon in straw. The ASTM Standard Method for Proximate Analysis of Coal and Coke (D-3172-73 through D-3174-82 and D-3175-82) were used. As straw is a highly volatile fuel, the modified version for sparkling fuels was used. Thus, the values of volatiles and ash were determined on dry matter basis. The fixed carbon was then calculated by the difference.

Ultimate analysis

Ultimate analysis was performed on ground-oven dried straw samples to determine the elemental composition. The weight fraction of carbon, hydrogen, nitrogen, sulfur, chlorine and arsenic were determined. The weight fraction of oxygen in the straw samples was calculated by the difference. Carbon, hydrogen and nitrogen weight fractions were determined using Perkin-Elmer Model 240 CHN Elemental Analyzer. Sulfur was determined using LECO Induction Furnace Method. Chlorine was

determined by following Mercuric Nitrate Method as given in Standard Methods for Examination of Water and Wastewater (APHA, 1980). Arsenic was determined by following Silver Diethyl-Dithiocarbamate Method as given in Official Methods of Analysis (Williams, 1984). The Standard Test Method for Ash in Wood (D-1102-84) was followed to determine the ash percentage in the straw sample.

Ash composition analysis

Ash compostion analysis was performed on the ash samples obtained from straws. The weight fractions of silica, potassium calcium, phosphorus, magnesium, sulfur, chlorine, sodium, aluminum, iron, and zinc and their oxides were determined. The oxides of silicon, aluminum, iron, calcium, magnesium, sodium and potassium were determined using the method given by Shapiro (1975) for rapid analysis of silicates, carbonate and phosphate rocks. Silica was determined by calorimetric analysis using the Molybdenum Blue Method. The oxides of aluminum, calcium, magnesium, sodium, potassium and iron were determined by atomic absorption (Abbey et al., 1974). Phosphorus oxide was determined using the method given by Shapiro (1975). LECO Induction Furnace method was used to determine the sulfur.

Ash Fusibility

Ash fusibility tests were performed on ash samples obtained from straws. The ASTM Standard Test Method for Fusibility of Coal and Coke Ash (D 1857-68) was used for conducting the tests. The initial deformation temperature, softening temperature, hemispherical temperature, and fusion temperatures, in the oxidizing and reduction modes were determined.

RESULTS AND DISCUSSION

PHYSICAL PROPERTIES

Moisture Content

The moisture content results are presented in Table 2. The values ranged from 10 to 18 %. This was very much within the range reported in the literature of 10-20% (Jenkins and Sumner, 1986). Higher moisture content values of 17-18% were observed with the rye varieties. This was due to rainy conditions during the harvesting period.

The moisture content of straw substantialy affects its quality as a fuel source. At high moisture, excess losses of dry matter of straw may occur because of microbial activities in the straw. Spontaneous combustion of straw bales stored at high moisture contents may also occur as reported by Jenkins and Sumner, 1986; and Dobie et al.,(1977). An increase in moisture content of the straw decreases its heat value which reduces the conversion efficiency of the system as a large amount of energy is used for vapourization of the fuel moisture during conversion. Thus, a dry fuel material is preferred for combustion process whereas a certain amount of fuel moisture is beneficial for gasification.

Table 2. Moisture content of straw at the time of harvesting and collection

Straw	Moisture Content (%)
Wheat:	
Max	12
Absolvent	13
Monopol	10
Vuka	12
Barley:	
Kadeth	12
Laurier	11
Leger	15
Oats:	
Sentinel	12
Shaw	10
Tibor	10
Rye:	
Kustro	17
Danko	18

The values are the average of 5 measurements.

Bulk Density

The average bulk density of the small bale of straw (850 x 500m x 3500) was 67 kg/m^3 for wheat, 70 kg/m^3 for barley, 63 kg/m^3 oats and 60 kg/m^3 for rye. These values are much lower than those reported in the literature (112-130 kg/m^3) (Jenkins and Sumner, 1986, and Miles and Miles, 1978). This may be due to the differences in reported moisture content during the time of harvesting.

Particle Size Distribution

The results of the weight, length and width distribution of chopped straw are presented in Table 3. The majority of straw (60%) have a length ranging from 3-35 mm and a width ranging from 1.5 to 2.0 mm. This was considered very suitable for gasification process. It was also handled very easily by the auger feeding system.

For efficient thermochemical conversion processes, it is generally preferred to use a uniform feedstock with respect to particle size, particle size distribution and particle shape. However, this requirement may differ from process to process. For example, a too large particle size may cause secondary reactions to occur within the particles that may lead to the formation of undesired products such as char and tars. On the other hand, if the particle size is too small, it may not be retained in the reaction zone long enough for complete conversion, thereby resulting in low conversion efficiencies. Particle size, size distribtion and shape also cause fuel flow

problems in the reactor, thereby causing improper and incomplete conversion (Miles, 1982).

Table 3. Straw weight, length and width distribution

Sieve Number	Straw (%)*	Length (mm) Range	Length (mm) Average	Width (mm) Range	Width (mm) Average
1	2.9	30.0-59.0	42.6	3.0-5.0	3.8
2	23.4	10.0-35.0	22.5	2.0-3.0	2.6
3	35.0	3.0-19.0	13.3	1.5-2.0	1.7
4	26.3	2.0-13.0	9.0	1.0	1.0
5	7.6	1.1- 5.0	2.0	0.2	0.2
6	4.1	0.1- 2.0	0.5	0.1	0.1
pan	0.8	dust	dust	dust	dust

* percent of total weight

THERMOCHEMICAL PROPERTIES

Heating Values

Heating value is usually expressed as higher heating value (HHV) and lower heating value (LHV). The higher heating value is measured using the adiabatic oxygen bomb calorimetric. The lower heating value is calculated from the higher heating value using the following relationship (Ebeling and Jenkins, 1985).

$$LHV = [HHV\ (1 - MC) - X\ (MC) - (1 - MC)]\ \frac{18\ H}{200} \quad (1)$$

where:

MC = the moisture content of fuel wet basis
X = the latent energy of vaporization for water
H = the hydrogen percentage by weight dry basis

The higher and lower heating values for 12 straw samples are presented in Table 4. The average higher heating value for the four cereal crops ranged from a low of 18.84 MJ/kg (oats) to a high of 19.63 MJ/kg (wheat), with percent variation of 4.2. However, the ash content of straw from oats and barley was higher than that of wheat straw. This confirmed the fact that increases in ash content results in lower heat value of the fuel. Chornet et al. (1980) calculated the calorific value for various straws using the relationship described in equation 1. The ranges of heating value for wheat , barley, oats and rice straws from these studies were: 16.49-17.51, 16.24-17.50, 16.67-17.90, and 13.76-16.28 MJ/kg, respectively. The variation in heat values for all types of different straws was about 30% which is much higher than that found in this study.

Proximate Analysis

Proximate analysis provides the weight fractions of volatiles, ash, and fixed carbon in fuels. The results of the proximate analysis conducted on 12 straw samples are presented in Table 5. Volatile matter and ash concentrations

Table 4. Heat value of straw (MJ/kg)

Straw	Heat Value: Higher Heating Value	Heat Value: Lower Heating Value
Wheat:		
Max	19.62	18.38
Absolvent	19.59	18.31
Monopol	19.96	18.71
Vuka	19.36	18.29
Barley:		
Kadeth	18.18	17.07
Laurier	18.96	17.76
Leger	19.38	18.20
Oats:		
Sentinel	18.96	17.66
Shaw	19.50	18.21
Tibor	18.98	17.80
Rye:		
Kustro	19.36	18.15
Danko	19.25	17.95

were determined as weight percentage on dry basis. Fixed carbon was then calculated by difference. The concentration of volatile matter varied from 77.04% to 79.85% for wheat, from 73.84% to 82.141% for barley, from 75.65% to 81.54% for oats and from 82.35% to 83.02% for rye. The average volatile matter of straw from the four cereal crops ranged from a low of 73.84% (oats) to a high of 83.02% (rye), with a 5.0 percent variation. In the present study, higher volatile matter was found in different cereal straw samples. Ebeling and Jenkins (1985) reported lower volatile matter contents for wheat and barley straws (71.30% and 68.8%, respectively).

The ash content of straw varied from 3.09% to 4.81% for wheat, from 4.22% to 7.32% for barley, from 1.80% to 5.06% for oats, and from 1.97% to 3.05% for rye. The overall range of ash content of all 12 samples was from a low of 1.97% rye (Kustro) to high of 7.32% barley (Kadeth). The percent variation in ash content of all samples was 271.6%. These results showed a wide variation in the ash content of different cereal straw samples. However, the ash contents of wheat and barley straw were lower than that reported by Ebeling and Jenkins (1985).

The range of fixed carbon varied from 16.76% to 18.15% for wheat, from 13.29% to 18.84% for barley, from 16.6% to 19.29% for oats and from 14.00% to 15.01% for rye. The fixed carbon range for all 12 samples was from 13.29% barley (Laurier) to 19.29% oats (Tibor), with a 45.1 percent variation. The results clearly indicated that the variation among the crops was more wide than among the varieties of the same crop. However, the fixed carbon of wheat and barley, measured in this study was lower than the values reported by Ebeling and Jenkins (1985).

Table 5. Proximate analysis of straw

Straw	Proximate Analysis (% dry basis)		
	Volatile Matter	Fixed Carbon	Ash
Wheat:			
Max	79.61	16.76	3.63
Absolvent	79.85	17.06	3.09
Monopol	77.80	17.61	3.59
Vuka	77.04	18.15	4.81
Barley:			
Kadeth	73.84	18.84	7.32
Laurier	82.41	13.29	4.30
Leger	81.48	14.30	4.22
Oats:			
Sentinel	78.88	17.04	4.08
Shaw	81.54	16.66	1.80
Tibor	75.65	19.29	5.06
Rye:			
Kustro	83.02	15.01	1.97
Danko	82.35	14.60	3.05

Ultimate Analysis

Ultimate analysis of straw provides the weight fractions of its elemental consitiuents. The major elemental constituents of straw are: carbon, oxygen, and hydrogen. Low concentrations of nitrogen, sulfur, chloride and arsenic can also be found. The major elements are important in assessing the heat value and the suitability of the material as fuel. The other elements provide information on production of undesirable products during the thermochemical conversion process with regard to environmental pollution problems. The results of the ultimate analysis conducted on 12 straw samples are presented in Table 6. The weight percentages of carbon, hydrogen, nitrogen, sulfur, chlorine and ash were determined in dry basis. Arsenic content of straw samples was also determined but it was found to be less than 0.01 percent in all samples and, therefore, is not reported in the table. The oxygen was calculated by difference.

Carbon: The carbon percentage varied from 44.26% (wheat-Vuka) to 46.61% (rye-Kustro) with a 5.3 percent variation among all 12 samples. The variation of carbon content among the varieties of a given cereal crop was marginal. The average carbon content of the four crop straws were: 45.56% for wheat straw, 45.34% for barley straw, 45.41% for oats straw, and 46.14% for rye straw.

Hydrogen: The hydrogen content of straws from different varieties of wheat, barley, oats and rye were: 4.97%-5.92%, 5.12%-5.61%, 5.51%-6.02% and 5.62%-6.04% respectively. The percent variation for hydrogen content of different straw varieties of the four crops were 19.1% for wheat, 9.6% for barley, 9.2% for oats and 7.5% for rye. The average hydrogen content of straw from wheat, barley, oats and rye was 5.61%, 5.39%, 5.84% and 5.84% respectively. The percent variation of average hydrogen contents of straw from different cereal crops was only 8.3%.

Oxygen: The oxygen percentage was 44.15%-44.68% for wheat straws, 41.59%-44.57% for barley straw, 42.62%-46.52% for oats straw, and between 45.14%-45.85% for rye straw. The average oxygen content of straw from wheat, barley, oats and rye was 44.30%, 43.41%, 44.20% and 45.50%, respectively. The percent variation for oxygen content of different straw varieties of wheat, barley, oats and rye was 1.4%, 7.2%. 9.2% and 1.6%, respectively. The percent variation of the average oxygen content among the crops was only 4.8%.

Nitrogen, sulfur and chlorine: Nitrogen, sulfur and chlorine percentages in the straw samples were very low. The sum total of the three constituents was less than 1.5 percent in all samples. Nitrogen varied from 0.13% to 1.33%, sulfur from 0.05% to 0.19%, and chlorine from 0.009% to 0.332%. The measured values of these three constituents were in the ranges reported by Ebeling and Jenkins (1985).

Ash composition:

The composition of ash from straw samples is presented in two forms: as mineral elements percentage by weight (Table 7) and as oxides of the mineral elements percentage by weight (Table 8). The major mineral elements found in the straw ash samples were : silicon, potassium, calcium, phosphorus, magnesium, and aluminum. Small amounts of iron, sodium, sulfur and zinc were also detected. A wide variation of the mineral elements in the straw ashes from the different varieties of different cereal crops under study was observed. The sum total of weight percentages of all mineral elements in straw ashes was between 50.98% and 67.83%. A wide variation of straw ashes in terms of constituent mineral oxides was observed. The sum total of all major mineral oxides present in straw ashes ranged from 82.06% to 99.27% on 100 basis. This confirmed the notion that the constituents of straw ashes do exist in forms other than elements.

Silicon oxide (SiO_2) and potassium oxide (K_2O) percentages in the straw ash varied over a wide range among the varieties of a given crop as well as among crops. SiO_2 varied from 14.75% to 65.54% whereas K_2O ranged between 8.00% to 51.03%. The composition of straw ash samples obtained from a particular location were found to be more consistent. The consistency in straw ash composition from a particular location might be due to common soil, climate, irrigation practices and fertilizer applications on the farm.

Ash fusibility:

Results of the ash fusibility tests conducted

Table 6. Ultimate analysis of straw (weight % on dry basis).

Straw	C	H	O	N	S	Cl	Ash
Wheat:							
Max	46.04	5.76	43.79	0.83	0.08	0.012	3.49
Absolvant	45.96	5.92	44.78	0.34	0.12	0.014	2.87
Monopol	45.97	5.78	44.15	0.55	0.12	0.018	3.41
Vuka	44.26	4.97	44.48	1.16	0.13	0.048	4.95
Barley:							
Kadeth	44.54	5.12	41.59	0.82	0.19	0.332	7.41
Laurier	45.47	5.61	44.57	0.20	0.12	0.009	4.02
Leger	46.01	5.45	44.07	0.39	0.10	0.010	3.97
Oats:							
Sentinel	46.30	6.02	43.47	0.13	0.11	0.019	3.95
Shaw	45.00	6.00	46.52	0.42	0.05	0.023	1.99
Tibor	44.94	5.51	46.62	1.33	0.16	0.052	5.39
Rye:							
Kustro	46.61	5.62	45.85	0.14	0.07	0.012	1.70
Danko	45.67	6.04	45.14	0.33	0.097	0.017	2.71

Table 7. Mineral elements composition of straw ash (% by weight)

Straw Ash	Si	K	Ca	P	Mg	Al	Fe	Na	S	Zn	Total
Wheat:											
Max	19.20	19.81	8.09	2.60	3.24	0.57	0.44	0.52	0.58	0.05	55.10
Absolvant	14.99	21.11	10.76	4.21	3.15	0.28	0.60	1.23	1.01	0.10	57.44
Monopol	12.98	30.00	7.71	2.84	2.53	0.39	0.53	0.72	0.99	0.16	58.85
Vuka	12.72	42.35	6.02	2.40	1.85	0.33	0.41	0.81	0.84	0.10	67.83
Barley:											
Kadeth	12.18	33.69	4.22	2.66	1.44	0.61	0.43	0.63	0.80	0.04	56.70
Laurier	24.74	6.64	8.42	3.16	2.58	2.54	1.63	0.60	0.65	0.10	51.06
Leger	25.52	7.60	7.13	3.16	2.59	2.96	1.96	0.59	0.65	0.09	52.25
Oats:											
Sentinel	31.21	8.93	2.69	1.31	1.28	2.80	1.74	0.72	0.28	0.02	50.98
Shaw	16.04	21.37	6.32	2.09	4.00	1.15	1.00	1.45	0.30	0.03	53.75
Tibor	7.02	34.01	6.37	3.77	3.22	0.15	0.17	0.55	0.85	0.04	56.15
Rye:											
Kustro	19.20	15.25	11.30	2.78	3.29	0.76	1.00	1.15	0.46	0.06	55.25
Danko	22.40	11.55	5.80	3.93	2.44	3.12	1.76	0.70	0.43	0.06	52.19

Table 8. Mineral oxides composition of straw ash (% by weight).

Straw Ash	SiO_2	K_2O	CaO	P_2O_5	MgO	Al_2O_3	Fe_2O_3	Na_2O	SO_3	ZnO	Total
Wheat:											
Max	40.33	23.87	11.32	5.95	5.37	1.08	0.63	0.70	1.45	0.06	90.76
Absolvant	31.47	25.43	15.05	9.65	5.22	0.54	0.86	1.66	2.52	0.12	92.52
Monopol	27.26	36.15	10.79	6.50	4.19	0.73	0.76	0.97	2.47	0.20	90.02
Vuka	26.71	51.03	8.43	5.50	3.07	0.63	0.59	1.09	2.10	0.12	99.27
Barley:											
Kadeth	25.59	40.59	5.91	6.10	2.39	1.16	0.62	0.85	2.00	0.05	85.26
Laurier	51.96	8.00	11.78	7.25	4.27	4.81	2.33	0.81	1.62	0.12	92.95
Leger	53.59	9.16	9.98	7.25	4.30	5.60	2.81	0.79	1.62	0.11	95.21
Oats:											
Sentinel	65.54	10.76	3.76	3.00	2.13	5.30	2.49	0.97	0.70	0.02	94.67
Shaw	33.68	25.75	8.85	4.80	6.63	2.18	1.43	1.95	0.75	0.04	86.06
Tibor	14.75	40.98	8.92	8.65	5.33	0.28	0.24	0.74	2.12	0.05	82.06
Rye:											
Kustro	40.31	18.37	15.81	6.37	5.46	1.44	1.43	1.55	1.15	0.07	91.96
Danko	47.05	13.92	8.11	9.00	4.05	5.89	2.52	0.95	1.07	0.07	92.63

on four straw ash samples are presented in Table 9. The results obtained from the tests on ash fusibility in oxidizing atmosphere indicated that the initial deformation temperature varied from 921°C wheat (Max) and 1043% oats (Sentinel), the softening temperature varied from 1043° C barley (Kadeth) to 1255°C oats (Sentinel), the hemispherical temperature varied from, 1088°C for barley to 1339°C for oats and the fluid temperature varied from 1172°C for rye to 1462°C for oats. The variation in ash fusibility temperatures could be attributed to the variations in composition of the ashes. The effect of ash composition on ash fusibility temperatures was also reported by Sondreal and Ellman (1975). The ash fusibility temperatures obtained in oxidizing atmosphere indicated that the temperatures in straw combustors must be kept below 900°C to avoid slagging problems.

The results obtained from the tests on ash fusibility in reducing atmosphere showed that the initial deformation temperatures for four straw ash samples varied from 904°C wheat (mas) to 1009°C oats (Sentinel), the softening temperature was between 1127°C and 1288°C, the fluid temperature varied from 1127°C barley (Kadeth) to 1345°C oats (Sentinel). The ash fusibility temperatures for all ash samples were lower in reducing atmosphere than in oxidizing atmosphere. During gasification, the reducing atmosphere is predominant. This indicated that the temperature during gasification of straw must be kept below 900°C to avoid slagging problems in the gasifiers.

Table 9. Deformation of fluid temperature of straw ash in oxidizing and reducing atmospheres

Straw	Temperature (°C)							
	Initial Deformation		Softening		Hemi-spherical		Fluid	
	O	R	O	R	O	R	O	R
Wheat	921	904	1054	938	1133	1127	1188	1199
Barley	987	943	1043	976	1088	1009	1155	1127
Oats	1043	1009	1225	1199	1339	1288	1462	1345
Rye	931	915	1077	1015	1105	1088	1172	1177

O = oxidizing atmosphere
R = reducing atmosphere

The varieties are Max, Kadeth, Sentinel, Kustro for wheat, barely, oats and rye, respectively.

SUMMARY AND CONCLUSIONS

Cereal straws have a large potential as fuel in combustion and/or gasification systems. The development of proper design of these systems require thorough understanding of the physical and chemical properties of the fuel material. The various aspects of physical and chemical properties of four major cereal straws (wheat, barley, oats and rye) were discussed. A wide variation in the reported values of physical and chemical properties of cereal straws has been observed. These wide variations in certain straw properties is more likely due to different methods and techniques used for harvesting, handling and storage of biomass rather than intrinsic properties of the straw. It is therefore recommended that standard methods should be used for performing physical and thermochemical analyses and reporting the data.

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CATALYTIC DECOMPOSITION OF BIOMASS TAR

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SUMMARY

INTRODUCTION

RESULTS

DISCUSSION

CATALYTIC DECOMPOSITION OF BIOMASS TAR

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On line treatment of the tars in the gas from a large biomass fueled gasifier was successfully carried out, using a wide range of catalysts. Over 98% of the tar was decomposed with Ni/Co/Fe and LZ-Y82. While not quite as efficient, limestone, magnesium oxide and alumina could produce similar results but with a greater mass of catalyst. The catalysts lost some activity due to carbon build-up.

Nous avons réussi, avec une grande gamme de catalyseurs, à traiter directement en circuit les goudrons contenus dans le gaz produit par un gros gazéificateur alimenté avec de la biomasse. Plus de 98% des goudrons étaient décomposés à l'aide de Ni/Co/Fe et de LZ-Y82. Même si le calcaire, l'oxyde de magnésium et l'alumine ne sont pas aussi efficaces, ils permettent d'obtenir des résultats semblables mais en présence d'une grande masse de catalyseur. Les catalyseurs perdaient une partie de leur activité en raison de l'accumulation de carbone.

INTRODUCTION

Gasification of biomass to recover energy, has been utilized for a broad range of commercial applications. These include:

- direct combustion for drying or calcining in rotary kilns
- generation of electricity, by directing the gas into a diesel generator
- firing the low BTU gas into a boiler for steam raising
- generating a synthesis gas for use in chemicals production.

In many of these applications, tar, which is co-produced with the gas, remains in the vapour phase and is combusted with the gas. However, if there is a need to cool the gas for pipelining, diesel power generation or chemicals manufacture, then the tar can create problems. The most obvious is deposition of the material on pipelines, ducts and equipment which eventually foul and plug up. Even when these problems can be avoided, the tar liquefies primarily as an insoluble mass in the aqueous condensate. Unfortunately, in this form, it cannot be discharged directly to a watercourse without extensive and expensive treatment.

One alternative to treatment in the liquid phase, is to catalytically decompose the tar into smaller molecules while it is still a vapour. This has been proposed by a number of workers in the field, including Black (1979), Donnot (1981) and Reed (1988). Trials with relatively simple catalysts such as limestone and dolomite, have been successful. However these tests have been quite limited in scope. Additional information is required to provide more fundamental engineering data for scale-up purposes.

The testing of a large demonstration biomass gasifier at St. Juste de Bretenieres, Quebec provided an opportunity to obtain this information under conventional operating conditions.

With funding from the Bioenergy Development Program of Energy, Mines and Resources Canada, a test program was conducted to elaborate on the catalytic approach.

PREVIOUS WORK

A review of the literature revealed that while little work had been directed towards tests with operating systems, much effort had gone into tests using vapourized coal tar, primarily by Wen (1983) and Baker (1985). The highlights of this work are:

- Molecular sieves with large pore openings, such as LZ-Y82 and 13-X, were very effective.
- Catalysts are quickly de-activated due to carbon deposition in the pores.
- High conversions (> 95%) can be obtained.

PROCEDURE

The intent of the program was to utilize the gas produced by the Biosyn gasifier during part of its normal test program. This particular gasifier was designed to operate at pressures up to 1700 kPa and temperatures in the range 750 - 900 C with both air and oxygen. To simplify the catalytic test program, the gasifier operating conditions were limited to 200 kPa and 800 C with air being used as the oxidising medium.

The test apparatus consisted of a gas conditioning system, a series of parallel packed bed reactors and a condensation train.

The gas conditioning system comprised a heat traced sampling system including an Inconel probe designed to minimise solids entrainment and a set of sintered Inconel filtering elements, complete with a backflush system designed to provide on-line cleaning of the filter units. Finally, the cleaned gas was reduced to a constant pressure by a high temperature control valve. All of this system was heat traced to 450 C and designed to accept 1700 kPa gas at 850 C.

The conditioned gas stream was then directed to the reactor assembly which contained 5 independently heated, fixed bed reactor assemblies, 90 cm x 1.3 cm dia. The reactors which were Alonized Inconel 600 tubes to minimize wall effects, were designed to operate at controlled temperatures up to 1000 C and were fitted with pressure, temperature and flow measuring equipment. A sixth reactor similar to the above, but without catalyst, was also included to provide a baseline sample for comparison. The entire assembly was contained in an oven at 450 C.

Gases leaving the reactor system were condensed in a series of large glass condensers cooled by recirculating chilled methanol. The condensate was collected in a flask and the gases were directed to a fibre filter and a set of six dry test meters. The gases were then vented to atmosphere.

The equipment, including the filters, was rinsed with methylene chloride at the end of each test and the washings retained for later analysis. The condensate was extracted with methylene chloride, dried and the solvent evaporated. The residue (tar) was then weighed to provide the total weight of tar recovered.

RESULTS

Fifteen different catalysts were tested over the temperature range 600 - 800 C. The catalyst properties are shown in Table I. In this initial screening program, the catalyst weight remained fixed at 10 g and the duration of the tests was one hour. Some of the results are summarized in Table II. The inlet tar concentration was taken from the sixth untreated sample stream. In spite of the fact that efforts were made to ensure that the gasifier was operated at constant conditions, the tar concentration in the gas leaving the unit showed some variation.

Based on these initial tests, two further sets of tests were carried out. In the first of these, the effect of time on the rate of catalyst decay was monitored by analyzing the material collected each hour over a six hour operating period. These results are shown in Table III.

In the final set of tests, the residence time was increased to determine the effect on conversion, to provide some indication of reaction kinetics.

In every test, the catalyst was covered with carbon and in many cases there was a significant weight increase, 20% or more.

In addition to the gravimetric measurement of tar content, the gas was visually observed as it flowed through the condensers. In general terms, the visual observations matched the gravimetric data. In most instances, the condensed liquid was brown and mist was visible. However, in the case of activated carbon, pure white crystals separated from the gas and little or no mist was present.

DISCUSSION

Heterogeneous catalytic reactions involve a number of sequential steps, including bulk phase mass transfer, diffusion, adsorption and surface reaction, all of which make kinetic analysis quite complex. A quick scan of the data reveals some interesting points:

- Some reaction rates increased with temperature, while others decreased.
- Build-up of carbon on various catalysts reduced activity at quite different rates.
- In one instance, increasing catalyst weight (residence time) did not markedly affect outlet concentration.

From this broad overview and within the range of conditions tested, it is reasonable to suggest that bulk phase mass transfer is not an important parameter and, in most instances, pore diffusion does not appear to be a rate limiting factor. On the other hand, chemisorption does appear to influence the overall rate of reaction.

With the exception of tar, all of the potential reactants and products are in sufficient excess that the surface reaction can be treated as a pseudo mono molecular reaction with tar as the active species. Under these conditions, the reaction rate can be described by

$$-\frac{dA}{dt} = \frac{K.A}{\frac{K}{ka} + \frac{1}{kr} + \frac{K.A}{kr}} \qquad (1)$$

where A is the concentration of tar

K is the equilibrium constant for adsorption/desorption

ka is the rate constant for adsorption

kr is the rate constant for surface reaction

If Ka ≪ ka is chemisorption controlled, then,

$$-\frac{dA}{dt} = ka.A \qquad (2)$$

which is a first order reaction. Similarly, if Ka ≫ Kr then

$$-\frac{dA}{dt} = \frac{kr.K.A}{1 + K.A} \qquad (3)$$

which, if only a few of the reaction sites are occupied i.e. K.A ≪ 1, reduces to

$$-\frac{dA}{dt} = kr.K.A \qquad (4)$$

Again, this is first order reaction. Finally, if most of the available sites are occupied i.e. K.A ≫ 1 then

$$-\frac{dA}{dt} = kr \qquad (5)$$

In this instance, the reaction rate becomes zero order.

From the above analysis, it appears reasonable to evaluate the kinetics based on a pseudo-first order reaction and calculate the reaction rate constant. Obvious anomalies to this approach can be evaluated as they arise.

Effect of Temperature

Table II summarizes the effect of temperature on the reaction rate constant. The overall effect of temperature is indeterminate, increasing the rate constant in some instances, decreasing in others and also going through a maximum. This result is not consistent with surface reaction model and tends to support the fact that most of the reactions are chemisorption dominated. In the few instances where rate increased with temperature, the data were analyzed on the basis of an Arrhenius equation. Even in these cases, the activation energy was sufficiently small, < 10K cal/mole, as to support the view that the reactions are chemisorption dependent.

The activity of the catalysts in the range tested can be ranked as follows:

Ni/Co/Fe > Co/Mo > limestone > Fe/Mo > alumina > MgO > Mo > LZ - Y82 > activated carbon > SK500 > Co > Ni > Silica gel > LZ - Y52 > Mol Sieve 3A.

The last two substances showed very little activity.

Effect of Residence Time

Three of the more reactive catalysts were tested to evaluate the effect of increasing vapour residence time, by altering the catalyst weight. The results are shown in Table IV. Both Ni and LZ - Y52 appear to be well represented by 1st order kinetics. Further manipulation of the activated carbon reaction data suggests that a better kinetic fit is observed if a zero order reaction is assumed i.e. chemisorption controlled.

Catalyst Decay

A layer of carbon was observed on all of the catalysts after one hour of processing. To examine the effect of carbon build-up, certain of the catalysts were exposed for longer periods of time. The data were evaluated using a decay rate model involving the loss of active sites which resulted in the representation,

$$A = Ao \,.\, \exp(-kd.t)$$

where A and Ao are the activities at time t and time zero and kd is the decay rate constant. The results of the analysis are shown in Table V. Two of the catalysts, Ni and SK 500, decay quite rapidly while the remainder lose activity at a much slower rate.

CONCLUSIONS

The principal conclusions from the study are:

- Over 98% of the tar from a biomass gasifier can be decomposed by catalytic reaction.
- Limestone and Magnesia, while not quite as active as Ni/Co/Fe, are very cost effective.
- Tar decomposition catalysts decay at an exponential rate due to carbon build-up.
- The reaction rate appears to be controlled in most instances by the chemisorption of tar.

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TABLE I

CATALYST PROPERTIES

CATALYST	SUPPLIER	COMPOSITION	SUPPORT	SIZE	BULK DENSITY g/cc	SURFACE AREA m²/g	PORE VOLUME cc/g
ACTIVATED CARBON	ACROS	carbon	none	-20+30 mesh	0.470	-	-
ALUMINA	ACROS	99+% alumina	none	0.2mm pellets	0.740	100.000	0.400
COBALT	ACROS	20% cobalt	proprietary	3.2mm pellets	0.900	60.000	0.030
COBALT/IRON/NICKEL	ALFA	3.5% CoO 3.5% Fe2O3 3.0% NiO	alumina	0.2mm pellets	1.140	70.000	-
COBALT/MOLYBDENUM	ACROS	3% CoO 12% MoO3	alumina	3.2mm pellets	1.120	100.000	0.400
IRON/MOLYBDENUM	ACROS	11% Fe 50% Mo	proprietary	4.0mm pellets	1.140	-	0.290
LIMESTONE	BDH CHM.	84-3 CaCO3	none	-10+20 mesh	1.000	-	-
MAGNESIUM OXIDE	ACROS	99% MgO	none	3.2mm pellets	1.070	30.000	0.270
LZ-Y82	LINDE	50.0% SiO2 29.0% AlO3	none	1/16"x1/8"	0.630	620.000	-
LZ-Y82	LINDE	50.0% SiO2 29.0% AlO3	none	1/16"x1/8"	0.630	625.000	-
BK-500	LINDE		none	1/16"x1/8"	0.610	550.000	-
NOL. OIRS DA	ACROS		none	1/16"x1/8"	0.314	-	-
MOLYBDENUM OXIDE	ALFA	10% MoO	alumina	3.2mm pellets	1.110	90.000	-
NICKEL	PARK THERMAL	75 Ni	refractory	-10+30 mesh	0.300	-	-
SILICA GEL	ACROS	99.0% SiO2	none	-3+6 mesh	0.660	550.000	0.900

TABLE II

EFFECT OF TEMPERATURE ON TAR DECOMPOSITION

CATALYST	REACTOR TEMP. °C	GAS FLOW Nm3/hr	EXIT TAR LOADING g/Nm3	INLET TAR g/Nm3	CONVERSN %	RESIDENCE TIME (secs)	TAR FEED RATE g/hr	k s-1
ACTIV. C	600.000	0.100	5.200	13.402	53.000	0.440	1.340	1.735
ACTIV. C	700.000	0.122	0.727	13.430	94.581	0.340	1.633	6.377
ACTIV. C	800.000	0.094	1.273	13.310	90.445	0.371	1.250	6.200
ACTIV. C	900.000	0.087	1.753	10.321	83.017	0.400	0.884	4.337
ALUMINA	600.000	0.152	9.130	16.432	50.030	0.100	1.600	3.586
ALUMINA	700.000	0.147	1.000	10.402	88.114	0.182	1.631	10.407
ALUMINA	800.000	0.152	1.000	11.207	85.088	0.150	1.702	12.132
Co	600.000	0.122	1.030	16.402	94.400	0.371	1.270	5.000
Co	700.000	0.110	4.062	12.024	83.482	0.371	1.410	3.042
Co	800.000	0.100	10.073	8.877	-20.235	0.362	0.888	-0.510
Co/Mo	600.000	0.120	1.714	16.331	89.389	0.147	1.260	13.173
Co/Mo	600.000	0.120	1.024	10.078	89.783	0.189	1.212	11.647
Co/Mo	800.000	0.120	0.010	5.000	91.755	0.110	1.042	21.149
Fe/Mo	600.000	0.124	1.000	10.321	84.500	0.147	1.260	12.044
Fe/Mo	700.000	0.110	1.314	10.078	86.001	0.130	1.201	14.011
Fe/Mo	750.000	0.045	1.001	9.000	83.134	0.271	0.445	4.700
LIMESTONE	600.000	0.110	8.210	10.402	40.000	0.123	1.230	4.230
LIMESTONE	700.000	0.147	5.500	12.024	57.405	0.000	1.000	5.032
LIMESTONE	800.000	0.110	4.140	10.321	59.032	0.000	1.105	6.207
LIMESTONE	900.000	0.120	1.230	8.077	80.053	0.102	1.000	10.326
LZ-Y82	600.000	0.181	7.000	13.000	42.020	0.100	2.520	2.054
LZ-Y82	700.000	0.147	0.022	8.767	0.402	0.210	1.402	0.414
LZ-Y82	800.000	0.150	0.700	9.440	20.200	0.170	1.470	1.075
LZ-Y82	600.000	0.070	0.211	13.000	98.400	0.430	1.000	6.070
LZ-Y82	600.000	0.001	0.203	13.000	98.110	0.040	0.040	7.270
LZ-Y82	700.000	0.123	1.380	8.767	85.773	0.240	1.107	7.076
LZ-Y82	800.000	0.152	3.547	9.440	62.404	0.170	1.430	5.400
MgO	600.000	0.137	2.033	10.433	70.022	0.153	1.431	6.200
MgO	700.000	0.107	1.060	10.402	81.175	0.170	1.110	6.000
MgO	800.000	0.110	2.073	11.207	81.504	0.145	1.303	11.805
Mo	600.000	0.074	0.807	10.321	94.210	0.355	0.702	11.170
Mo	700.000	0.082	1.024	10.078	94.001	0.100	0.821	10.174
Mo	800.000	0.000	2.170	9.000	70.151	0.170	0.000	8.549
M. S. DA	600.000	0.132	0.153	13.402	30.430	0.220	1.701	2.100
M. S. DA	700.000	0.145	0.155	13.430	31.000	0.102	1.081	1.894
M. S. DA	800.000	0.127	0.305	13.310	30.000	0.107	1.001	2.473
Ni	600.000	0.112	5.000	10.402	44.422	0.321	1.100	1.774
Ni	700.000	0.125	4.000	10.402	52.400	0.300	1.300	2.703
Ni	700.000	0.123	3.725	12.024	71.174	0.375	1.000	4.537
Ni	800.000	0.110	4.010	8.077	45.724	0.207	0.900	3.131
Ni/Co/Fe	600.000	0.140	1.195	13.430	91.101	0.131	1.900	16.430
Ni/Co/Fe	600.000	0.045	1.730	13.000	87.550	0.417	0.043	5.000
Ni/Co/Fe	600.000	0.135	0.201	13.400	98.011	0.151	1.070	27.079
Ni/Co/Fe	800.000	0.131	1.500	13.310	88.500	0.122	1.000	17.487
SIL. GEL	600.000	0.000	2.137	10.433	79.010	0.301	0.014	4.100
SIL. GEL	700.000	0.104	4.377	10.402	58.110	0.200	1.000	3.604
SIL. GEL	800.000	0.102	6.040	11.207	30.021	0.200	1.120	1.060
BK-500	600.000	0.050	0.100	13.000	60.700	0.037	0.274	0.030
BK-500	700.000	0.100	0.000	10.402	41.740	0.317	1.041	1.707
BK-500	700.000	0.000	0.421	8.767	95.000	0.042	0.401	4.000
BK-500	800.000	0.002	0.305	9.440	96.773	0.153	0.000	7.070

TABLE III

EFFECT OF ON-STREAM TIME ON TAR DECOMPOSITION

CATALYST	REACTOR TEMP. °C	TIME ON STREAM mins.	EXIT TAR LOADING g/Nm3	INLET TAR g/Nm3	CONVERSN %	RESIDENCE TIME (secs)	TAR FEED RATE g/hr	k s-1
ACTIV. C	800.000	60.000	1.753	10.321	83.017	0.400	0.884	4.337
ACTIV. C	800.000	130.000	1.739	10.078	82.740	0.325	0.881	3.367
ACTIV. C	800.000	210.000	2.035	9.000	70.562	0.422	0.700	2.341
ACTIV. C	800.000	270.000	1.841	10.432	84.200	0.350	0.718	3.302
ACTIV. C	800.000	330.000	2.530	10.402	75.000	0.324	0.733	2.841
ACTIV. C	800.000	390.000	3.000	11.207	72.402	0.151	0.782	2.340
LIMESTONE	800.000	60.000	4.140	10.321	60.032	0.000	1.105	8.207
LIMESTONE	800.000	130.000	1.030	10.078	83.740	0.110	0.879	15.253
LIMESTONE	800.000	210.000	1.771	9.000	82.230	0.100	0.825	9.121
LIMESTONE	800.000	270.000	2.703	10.433	73.324	0.132	0.855	5.000
LIMESTONE	800.000	330.000	3.102	10.402	60.323	0.110	1.053	5.874
LIMESTONE	800.000	390.000	5.004	11.207	38.407	0.120	1.117	4.030
LZ-Y82	800.000	60.000	0.283	13.000	85.115	0.040	0.040	7.270
LZ-Y82	800.000	120.000	0.159	8.767	98.370	0.407	0.012	10.110
LZ-Y82	800.000	270.000	2.074	13.402	85.140	0.270	1.571	5.003
LZ-Y82	800.000	333.000	2.903	13.430	78.302	0.240	1.000	6.174
LZ-Y82	800.000	393.000	3.074	13.310	80.150	0.200	2.044	4.240
Ni	700.000	30.000	4.000	10.402	32.400	0.200	1.300	2.703
Ni	700.000	110.000	3.200	12.024	60.104	0.200	1.020	3.127
Ni	700.000	183.000	0.710	0.077	1.002	0.310	0.071	0.000
Ni	700.000	243.000	21.240	22.807	7.212	0.333	2.307	0.225
Ni/Co/Fe	800.000	60.000	1.730	13.000	87.550	0.417	0.043	5.000
Ni/Co/Fe	800.000	120.000	0.801	8.767	31.520	0.170	1.000	2.151
Ni/Co/Fe	800.000	210.000	0.601	0.440	20.204	0.100	1.002	2.000
Ni/Co/Fe	800.000	270.000	7.205	13.402	46.402	0.100	1.070	3.000
Ni/Co/Fe	800.000	333.000	10.007	13.430	24.000	0.100	1.043	1.700
Ni/Co/Fe	800.000	393.000	10.044	13.310	24.500	0.150	1.024	1.703
BK-500	700.000	50.000	0.000	10.402	41.740	0.317	1.041	1.707
BK-500	700.000	110.000	0.000	12.024	81.245	0.333	1.226	2.051
BK-500	700.000	183.000	7.010	0.077	15.328	0.300	0.700	0.632
BK-500	700.000	243.000	17.204	22.807	24.003	0.300	1.013	0.793

TABLE IV

EFFECT OF CATALYST WEIGHT ON TAR DECOMPOSITION

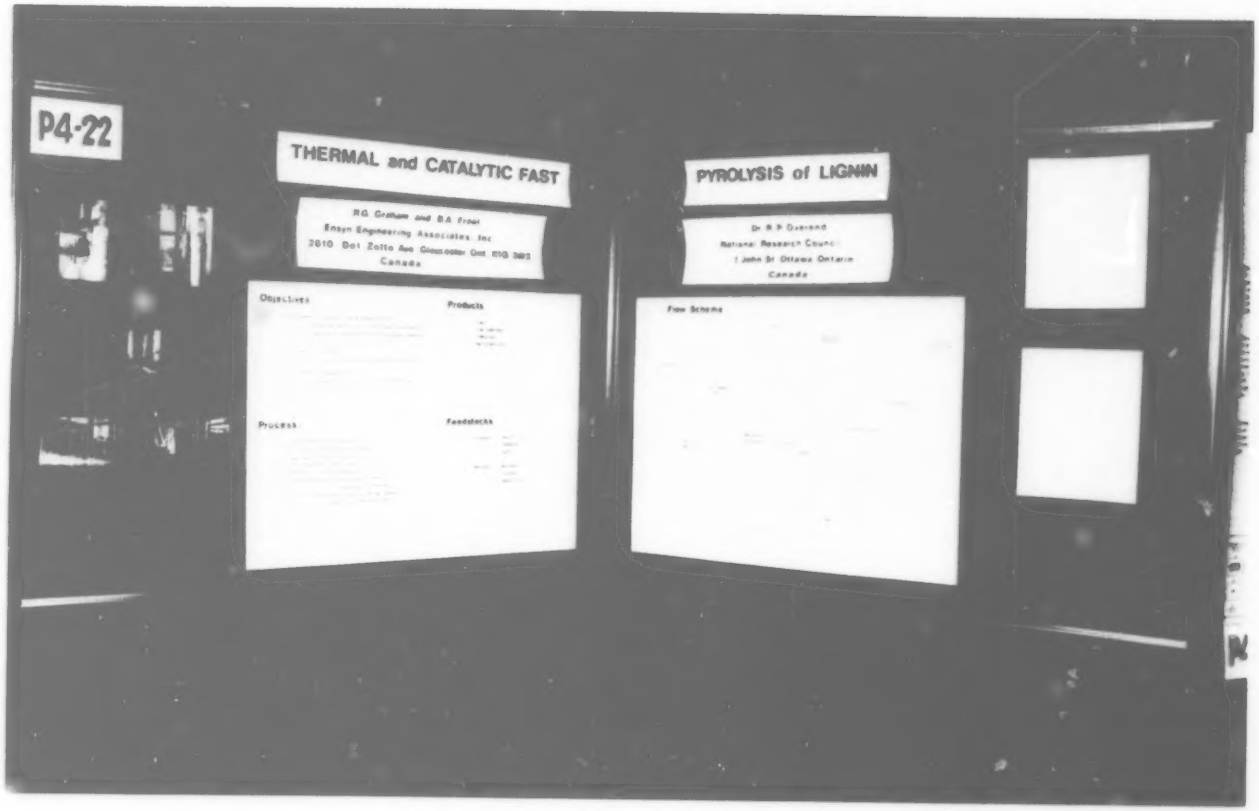
(Bed temperature = 800°C)

CATALYST	DURATION mins.	GAS FLOW Nm3/hr	EXIT TAR LOADING g/Nm3	INLET TAR g/Nm3	CONVERSN %	RESIDENCE TIME (secs)	TAR FEED RATE g/hr	k s-1
ACTIV. C	90.000	0.078	1.059	22.987	83.781	1.102	1.000	2.203
ACTIV. C	90.000	0.094	1.273	13.310	90.445	0.371	1.250	5.205
ACTIV. C	84.000	0.087	1.753	10.321	83.017	0.400	0.884	4.337
LZ-Y82	95.000	0.155	0.760	9.440	25.300	0.170	1.470	1.075
LZ-Y82	60.000	0.110	0.044	22.007	73.005	0.367	2.700	2.230
Ni	97.000	0.110	4.010	8.077	45.724	0.207	0.000	2.131
Ni	60.000	0.113	2.000	22.007	87.745	0.000	2.587	3.043

TABLE V

LOSS OF CATALYST ACTIVITY

CATALYST	DEACTIVATION RATE (t = mins.)	TEMPERATURE (C)	COEFFICIENT OF DETERMINATION (r2)
ACTIVATED CARBON	k = 4.20 EXP(-.00152 t)	850	.593
LIMESTONE	k = 10.35 EXP(-.00200 t)	850	.811
LZ-Y82	k = 10.00 EXP(-.00180 t)	850	.655
NICKEL	k = 8.42 EXP(-.0180 t)	700	.892
NICKEL/COBALT/IRON	k = 4.20 EXP(-.00221 t)	850	.387
BK-500	k = 3.26 EXP(-.00715 t)	700	.474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THERMAL and CATALYTIC FAST
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Objectives
Products
Process
Feedstocks
PYROLYSIS of LIGNIN
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Flow Scheme

THERMAL AND CATALYTIC FAST PYROLYSIS OF LIGNIN BY RAPID THERMAL PROCESSING (RTP)

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Systematic fast pyrolysis of lignin, isolated from steam-treated poplar wood via alkaline extraction, is being carried out in Ensyn's 10 kg/h (1 barrel per day) Rapid Thermal Processing (RTP) pilot plant. The yields of total liquid, gas and solid products are investigated as a function of residence time, reaction temperature, type of heat carrying particulate solids (i.e., catalytic vs. noncatalytic) and solids loading (the mass ratio of heat carrier to lignin. Products of interest include petrochemical intermediates (esp. olefins) in the gas and liquid phases. Mathematical modelling is being undertaken in cooperation with the National Research Council to adequately characterize the kinetics of the fast pyrolysis of lignin. As a complement to the main fast pyrolysis study, a theoretical heat transfer model is being evaluated as a tool to determine the largest biomass particle size that can be effectively pyrolyzed in the RTP reactor.

On procède, dans l'usine pilote à traitement thermique rapide de la Ensyn, d'une capacité de 10 kg/h (1 baril/jour), à la pyrolyse rapide systématique de lignine isolée, par extraction alcaline, à partir de bois de peuplier traité à la vapeur. On étudie les rendements en liquides, en gaz et en solides totaux en fonction du temps de séjour, de la température de réaction, du type de matières particulaires utilisées comme solides conducteurs de chaleur (c'est-à-dire catalytiques par opposition à non catalytiques) et de l'apport en solides (rapport masse des solides conducteurs de chaleur/masse de la lignine). Les intermédiaires pétrochimiques présents dans la phase gazeuse et dans la phase liquide comptent parmi les produits d'intérêt. On effectue des modélisations mathématiques en coopération avec le Conseil national de recherches, afin de caractériser convenablement la cinétique de la pyrolyse rapide de la lignine. En complément de l'étude principale sur la pyrolyse rapide, on évalue un modèle théorique simulant le transfert de chaleur, en vue de déterminer la taille maximale des particules de biomasse qui peuvent être pyrolysées efficacement dans le réacteur à traitement thermique rapide.

INTRODUCTION

The results of previous federal and private bioenergy research and development programs have demonstrated a need for the production of high value chemical and fuel products (i.e., olefins, BTX, SNG, CO/H2, etc.) from biomass. Although gasification, liquefaction and conventional pyrolysis have exhibited commercial potential in specific applications, their widespread implementation has not yet been realized. This is due in part to feedstock constraints (i.e., dispersed sources, low energy density, high transportation costs per unit energy value, relatively high comminution costs, etc.). It is also due to the low economic value of the product (often low-grade thermal energy) and the relatively low cost of the fossil fuels which they are expected to displace. The development of high value products could accelerate the near-term implementation of biomass processing plants by offsetting the feedstock constraints. This approach would also provide valuable process development and large-scale operating experience for the eventual commercialization of the lower value product applications (thermal energy, shaft power, etc.) when economic factors become favourable (i.e., if the costs of traditional petroleum fuels increase dramatically).

With these considerations in mind, the federal government (Enfor/EMR, NRC) funded a research project at the University of Western Ontario (UWO) involving rapid heat transfer for the fast pyrolysis of biomass. This system was ideal for fundamental process development and kinetic studies, not only for biomass conversion but also for additional applications involving rapid, high-temperature processes. The initial program dealt primarily with a fundamental investigation of the kinetics and optimization of high value gaseous products from powdered biomass

feedstocks with particular emphasis on cellulose pyrolysis. A relatively thorough investigation of the fast pyrolysis of cellulose was carried out in the temperature range of 650 to 900°C and at residence times between 50 and 900 milliseconds. A preliminary study of poplar and maple in powdered form was also initiated.

The UWO reactor system was significantly modified by Ensyn engineers, and was successfully integrated into a scaled-up pilot "Rapid Thermal Processing" (RTP) pilot plant, rated nominally at 10 kg/h or 1 barrel/day. The RTP pilot plant capacity is at least 20 times that of the original plant in London. Currently in progress is a project to scale-up the RTP reactor by a factor of 10. This third RTP system has a rated nominal capacity of 90 kg/hr (10 barrel/day) and will be in operation at Ensyn's Gloucester facility during the summer of 1989.

The experimental plan outlined in the present project was been drawn up in cooperation with companies representing both the petrochemical and petroleum industries. The current commercial interest is related both to the nature of the product, petrochemicals and high quality fuel gases, and the nature of the feedstock, primarily lignin. The petrochemical industry, for example, is interested in the fast pyrolysis of a variety of alternate feedstocks, including biomass, for applications either as fossil fuel substitutes or chemical synthesis feedstocks. The unsaturated and aromatic nature of lignin, consisting of a phenyl propane nucleus, could allow high yields of BTX and olefin gases from fast pyrolysis.

Petroleum companies currently involved in fuel alcohols are interested in finding high-value uses and markets for lignin "byproducts", particularly as a feedstock for conversion/upgrading processes. This interest stems from their current market for the use of ethanol as a fuel additive (i.e., a cosolvent and octane booster). The ethanol is currently produced from a bioconversion technology which processes non-lignocellulosic biomass (grain). The current drawback to the use of abundant and relatively inexpensive lignocellulosics (i.e., wood) is the lack of high-value uses and markets for the significant quantities of the lignin byproduct. The future of ethanol as a fuel additive is very bright and production could dramatically increase, since it is used to substitute for lead additives which are soon to be phased out.

OBJECTIVES

The general objective of the current R&D program is to continue to investigate the fast pyrolysis of biomass feedstocks (wood and lignin) to produce products which are of current commercial interest to several important industrial sectors in Canada. This paper is specifically concerned with the systematic investigation of the rapid pyrolysis of lignin feedstocks. These general objectives can be further subdivided into specific technical and process development segments which have been identified in consultation with petrochemical and petroleum industry technical personnel:

1. The systematic characterization of the production of net yields of gas, liquid and solid products from a commercial lignin feedstock via fast pyrolysis. Also included is the optimization of the production of valuable petrochemical feedstocks and fuel gases from lignin. Previous fast pyrolysis work systematically investigated cellulose and wood (poplar) pyrolysis but lignin characterization has not been carried out to any extent.

2. The development of a comprehensive heat transfer model for biomass feedstocks under fast pyrolysis conditions. The model would include a thorough assessment of the principle heat transfer mechanisms which are significant under these conditions, and would be compared to actual pilot plant trials using feedstocks of varying particle sizes.

3. The preparation of an overall kinetic model (either in the form of a First Order Model or suitable Kinetic Severity Function) which fits the data for wood, cellulose and lignin rapid pyrolysis/cracking (using data from prior, current and proposed experiments). This is an empirical modelling approach which is valuable for prediction of yields, process optimization and process control.

Although the objectives of the proposed program relate primarily to applied engineering and process development, it must be stressed that concurrently a significant contribution will be made to the "science" of pyrolysis, including mechanistic insights.

EQUIPMENT

The existing RTP pilot plant, including its principal components, is illustrated in Figure 1. The plant is rated nominally at 5 to 10 kilograms per hour. Hot solids (i.e., sand or catalyst) flow from a number of "heat carrier" feeders to the reactor system where they are injected into the rapid thermal mixer. The carbonaceous feed material (solid, liquid, or gaseous) is delivered from one of several interchangeable feeders (i.e., the "biomass feeder" in the present configuration) to the top of the reactor where it is injected into the cloud of turbulent hot solids. Extremely rapid heating of the feed material is achieved as the feed and hot sand or

catalyst particles are quickly and thoroughly mixed. After the fast, intimate mixing is complete, the feed and solid heat carrier pass through a tubular transport reactor, the length of which is adjusted to control the processing (residence) time.

The products are rapidly cooled in a transfer line after the hot solids are removed in a solids "catch pot" or drop-out vessel. Additional cooling is carried out in the primary (water-cooled) and secondary (dry ice-cooled) condensers, where condensation of vapours and recovery of liquids also occur. Parallel filters are used to collect persistent aerosols, and the clean gas is then directed through an orifice meter (to quantify the flow for mass balance closure). A fractional quantity of the product gas is continuously "bled" from the main stream to a gas sample bag for subsequent analyses. When the aerosol loading is particularly high, an electrostatic precipitator is installed between the condensers and the filters.

There are three identical heat carrier feeders which serve to heat up the sand or catalyst heat carrier and deliver it to the transport lines. Each feeder is about 1.2 meters long and 150 mm outside diameter (Sch 40 pipe; 6" nominal diameter), and can hold 30 kg (silica sand). The maximum feed rate is about 60 kg per hour (for each feeder) and the maximum temperature is 1100°C. Feeder control is accomplished via a sparger tube and a non-mechanical, high temperature "J" valve. A mechanical table feeder is used to supply the lignin, and has an inventory of about 4 kg. Solids pass from sealed hoppers through a double funnel system and are thereby metered onto a rotating table. Two fixed armatures sit near the surface of the round table and plough the solids off the outer circumference. From the table, the solids then fall into a conical chamber where they are picked up and carried into a transport line by nitrogen carrier gas. The overall range of the feed rate of the solids is controlled by setting the gap between the lower funnel and the table. Fine control is exercised by the rotatior speed of the table. Feed rates can be varied from 0 to about 10 kg per hour, and are independent of the transport gas flow rate and the solid heat carrier flow rate. The feeder is mounted on casters to allow for easy removal.

The reactor system consists of a rapid thermal mixer and two lengths of transport reactor - each of these having independent temperature control. Rapid mixing of the feedstocks with the solid heat carrier (i.e., sand or catalyst) takes place in the rapid thermal mixer, and chemical reactions are then allowed to proceed in the transport reactor sections. The first reactor is 1.2 m in length while the second is 0.6 m. The reactor system components are constructed of Sch 40 Inconel 601 (40 mm I.D./1.5" nominal).

The solids catch pot is an inertial separator constructed of stainless steel and can hold about 100 kg of hot solids. Separation of the gases from the solids is based on the lower momentum of the gas/vapour product (compared to the hot sand or catalyst) which can change direction more readily than the solids, and escape into the transfer line to be quenched directly with nitrogen gas.

The primary condenser is a water-jacketed carbon steel pipe (having both an inner and outer water-jacket) which is lined with a chemical resistant paint. The cooling water enters the condenser at about 19°C and cools the product to about 25°C. The secondary condenser is also a lined, carbon-steel pipe which is not jacketed but sits directly in an insulated dry ice bath. It has a tangential gas/vapour inlet which forces the products to the condenser wall where efficient heat transfer can occur.

To ensure the removal of any entrained condensed liquid or fine solid residue, a final filtration system is included in the product recovery stream. There are three parallel filters which are constructed of stainless steel, and have a pore size of 0.5 microns. They are housed in a single filter vessel. Each of these filter units are about 50 mm in diameter (outside) and about 0.5 m long.

RTP EXPERIMENTAL PROCEDURE

The furnaces which house the sand or catalyst heat carrier feeders, mixer and the reactor lengths are activated about 8 hours prior to an experiment. The heat carrier ovens are set at a temperature which is about 150°C greater than the desired reaction temperature. This temperature differential accounts for transport/reactor system thermal losses and provides the heat required to raise the feedstock from ambient to reaction temperature.

During the heat-up period, a number of system checks, calibrations and peripheral system activations are carried out:

- the gas chromatograph is turned on, brought to desired operating conditions, and calibrated using a known gas sample;
- the system is pressure-tested to detect and correct any leaks;
- nitrogen is allowed to continually purge the system of air and residual product gas;
- water is fed to the primary condenser water-jacket;
- the secondary condenser bath is filled with liquid CO_2;

- the gas sampling bag is purged and evacuated;

- the chart recorder for reactor temperatures is activated;

- computer programs are run to assist in setting the carrier gas flows (these allow selection of the desired residence time as a function of temperature and reactor volume).

Just prior to the beginning of the experiment, the following steps are taken:

- the quench gas (which cools the product stream) is delivered to the gas exit line;

- system transport gas (nitrogen) flow is initiated in the "bypass" mode;

- transport gas is delivered to the heat carrier feeders and the feeder vibrators are activated;

- the feeder transport gas is diverted to the heat carrier feeder, and solids flow is verified using a thermocouple;

- fluidization gas in the heat carrier feeding mechanism is adjusted until the desired reactor inlet temperature is reached;

- the reactor temperatures are monitored on the chart recorder to ensure that the desired setpoint has been realized.

The actual experiment begins when the biomass feeder is activated and the wood is delivered to the reactor system. At this point, the gas sampling bag valve is opened and a constant flow of product gas is bled from the main gas line to the gas bag. Orifice measurements for determining gas flow are taken every 30 seconds. System temperature, gas flows (via rotameters and an orifice meter) and pressures are monitored continually.

Sand heat carrier flowrates are adjusted as required, to maintain the desired reactor temperatures and to ensure isothermal conditions. After the desired quantity of biomass has been fed, the steady-state experiment is terminated when the biomass feeder is turned off. The data recorders, system furnaces and carrier gas flows are then shut down.

At least three gas samples are taken from the sampling bag and analyzed for hydrogen, carbon monoxide, carbon dioxide and C1 to C6. The C5/C6 fraction is analyzed as a single constituent. After gas analyses, the quantity of sampled gas is determined by evacuation into a vacuum tank of known, fixed volume.

The product recovery system (catch pot, cyclones, condensers, filters, transport lines, etc.) is disassembled and flushed with acetone to recover pyrolytic liquids. Fugitive solids which have been collected with the liquids are filtered from the solvent, quantified by gravimetry and then ashed for char determination. The filtered mixture of pyrolytic liquid and solvent is rotary-evaporated to recover and quantify the raw liquid product. Selected samples are sent to B.C. Research for analyses.

After cooling in the inert atmosphere of the catch pot, the bulk recovered solids are riffled, sampled and ashed to determine the solid residue (i.e., char) yield. Ashing is carried out (on the samples and a sand or catalyst "control") in a muffle furnace according to ASTM procedures.

The equipment is reassembled and the respective feeders are charged with fresh sand or catalyst, and biomass in preparation for the next experiment.

LIGNIN AND HEAT CARRIER CHARACTERIZATION

Lignin Feedstocks

The representative commercial lignin used in this project is a spray-dried sample which has been caustic-extracted from steam-treated poplar, supplied Iogen Corporation (Ottawa). The mean particle size is nominally 200 microns.

Noncatalytic Solid Heat Carriers

The noncatalytic solid heat carrier is simply F-40 grade non-porous silica sand supplied by Industrin, St. Canut, Quebec. The mean diameter particle size is 256 microns, and the moisture content is less than 0.5% by mass.

Catalytic Solid Heat Carrier

The catalytic solid heat carrier is DA-440 cracking catalysts supplied by W.R. Grace Company, Valleyfield, Quebec. The catalyst has a mean particle diameter of 69 microns and an activity of 83%.

PRELIMINARY RESULTS

The experimental portion of current lignin pyrolysis program was initiated early in 1989. Therefore, a limited number of systematic, steady-state experiments, using noncatalytic sand as the heat carrier, have been completed to date. A summary of the results of these preliminary experiments is given in Table 1.

Rapid pyrolysis experiments have been conducted in the temperature range of 500 to 850°C and at residence times between 200 and 900 milliseconds. The maximum gas yield thus far is about 32% of the lignin mass, at a temperature of

850°C and a residence time of 525 milliseconds. The maximum overall liquid yield is about 70 % of the lignin feed mass at 500°C and 870 milliseconds. The solid "char" yield ranged from 10 to 40 % of the mass of the lignin, and seemed to exhibit a maximum at intermediate temperatures of 550°C.

FUTURE WORK

Systematic experiments to investigate the rapid pyrolysis of lignin using catalytic and noncatalytic heat carriers will continue within the temperature range of 500 to 900°C and at vapour residence times between 200 ms and 1.5 s. The results will be fitted to an kinetic model. Optimum conditions of temperature and residence time will be determined for maximum yields of valuable petrochemicals (olefins) and potential liquid fuel additives (BTX). Samples will be sent to B.C. Research for elemental, moisture and GC analyses.

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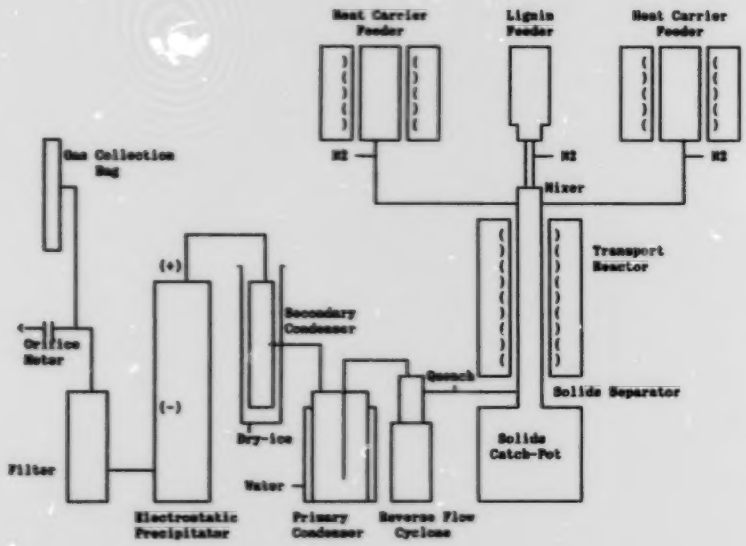
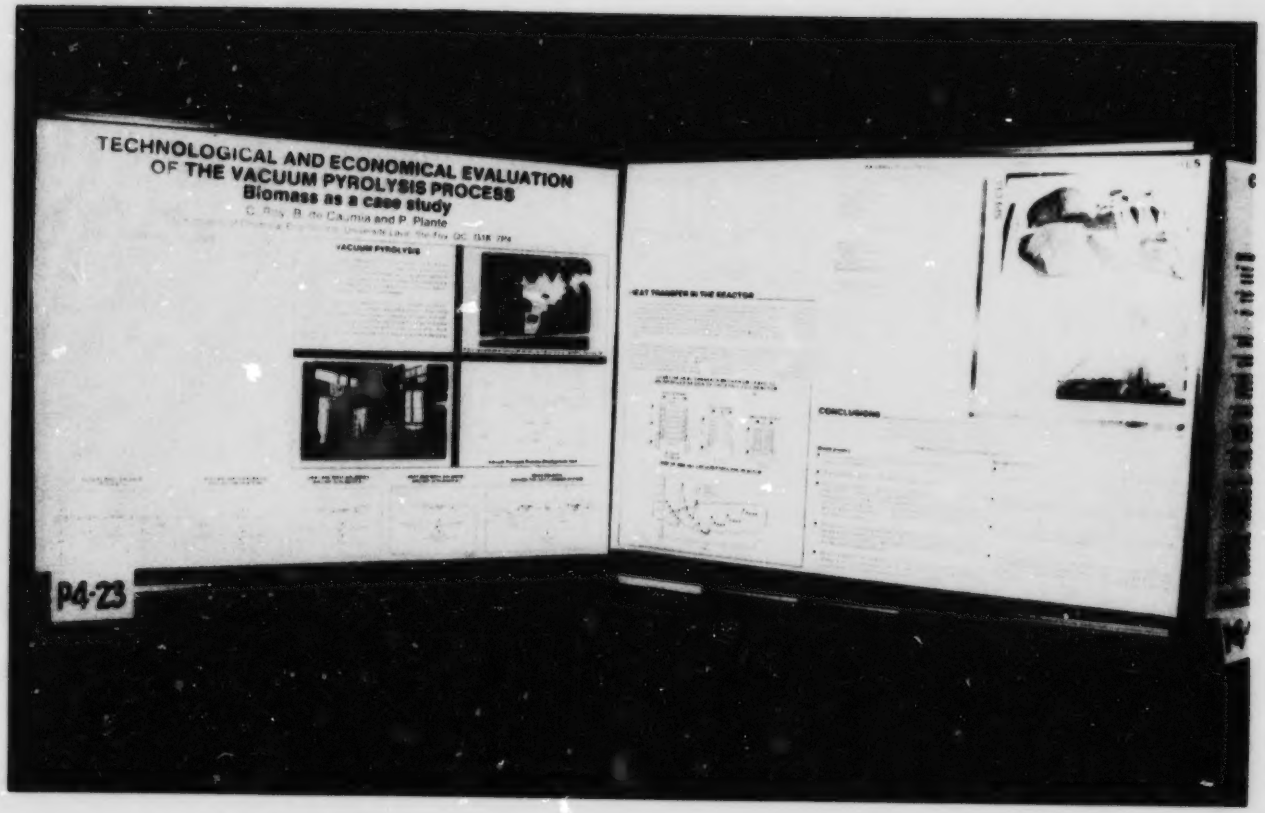


Figure 1. Rapid Thermal Processing Pilot Plant Schematic

Table 1. Summary of the Iogen Lignin Runs

RUN NUMBER	REACTOR TEMPERATURE (°C)	RESIDENCE TIME (ms)	PRODUCT YIELD (% by mass) Gas (%)	Liquid (%)	Solid (%)
IL-1	505	870	5.9	69.5	24.6
IL-2	550	418	12.5	53.1	34.4
IL-3	550	882	12.7	44.6	42.7
IL-4	550	291	10.5	51.4	38.1
IL-5	650	300	12.6	64.3	23.1
IL-6	700	380	26.0	60.0	14.0
IL-14	700	300	25.6	60.0	14.4
IL-17	850	525	32.2	57.2	10.6


TECHNOLOGICAL AND ECONOMICAL EVALUATION
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VACUUM PYROLYSIS
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EVALUATION OF THE VACUUM PYROLYSIS PROCESS
Biomass as a case study

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Vacuum pyrolysis has been used in our laboratories as an approach for the conversion of biomass (*e.g.*, wood), urban wastes (*e.g.*, scrap tires) and industrial wastes (*e.g.*, petroleum sludges) in valuable energy (*e.g.*, liquid fuels and charcoal) and chemical products (*e.g.*, food aromas and pharmaceutical compounds). A Process Development Unit using a multiple hearth furnace has been successfully operated at a throughput of 25 kg/h which led to the determination of the optimum process conditions for various feedstocks. A technical evaluation of the process has been conducted using forestry wastes as a case study.

La pyrolyse sous vide a été utilisée dans nos laboratoires pour la transformation de la biomasse (*e.g.*, le bois), des déchets urbains (*e.g.*, les pneus usagés) et les déchets industriels (*e.g.*, les boues pétrolières) en produits de valeur énergétique (*e.g.*, *des* combustibles liquides et charbons de bois) et chimique (*e.g.*, des arômes alimentaires et composés pharmaceutiques). Une Unité de Développement de Procédé comprenant un four à soles multiples a été opérée avec succès à un débit de 25 kg/h afin de déterminer les conditions opératoires optimales du procédé en fonction de diverses sources d'alimentation. On a effectué une évaluation technique du procédé en prenant les déchets forestiers comme cas-type.

STATUS OF THE PROJECT

The vacuum pyrolysis process has been under development since the early 1980's in our laboratories. Originally, the objective was to transform forestry wastes in oils and wood charcoal. Back in 1984, a new objective was incorporated which involved the separation and purification of the fine chemical by-products contained in these pyrolysis oils. A bench scale preparative liquid chromatography system has been built and the preliminary results have been presented by H. Pakdel *et al* during this Seminar. The pyrolysis process has been developed to the point that bark and sawdust wood wastes can now be continuously fed at a flowrate of about 30 kg/h in the reactor. This paper describes the performance of the pyrolysis reactor and the downstream associated equipment.

One special application of the process has been found for scrap tires. A pilot plant unit (200 kg/h) has been built and tested during fall 1987 in Saint-Amable near Montreal (see Photograph 1). The main products are a heating oil (55% by wt.), carbon black (25%) and steel (8%). The project has been momentarily stopped during 1988 due to the bankruptcy of the licensed company (Petro Sun Intern. Inc.). With the financial support of both Université Laval and Energy, Mines and Resources (Bioenergy Development Program), the project was continued at the P.D.U. level during 1988-89. The pilot plant phase will be continued during 1989 under the auspices of Petro-Tire Inc., Hamilton, Ontario for the used tire application.

EXPERIMENTAL

A diagram of the Process Development Unit (P.D.U.) used in this study is drawn in Figure 1 of the paper. The reactor was a six hearth furnace, 2 m in height and 0.7 m in diameter. It was

Photograph 1: Pilot plant vacuum pyrolysis unit used for recycling old tires in St-Amable, Qué.

Table 1 Yields and Mass Balances for Vacuum Pyrolysis of Wood

RUN	REACTOR TEMPERATURE (°C)	REACTOR PRESSURE (kPa)	YIELDS (wt. %, ash-free, dry wood basis) OIL	WATER	CHARCOAL	GAS	MASS BALANCE CLOSURE (%)
C010	425	1.6	46.4	18.2	24.2	11.2	96.7
C012	363	2.4	41.6	14.9	33.0	10.5	97.5
C014	450	3.3	45.8	17.0	25.6	11.6	96.1
C015	425	1.9	50.1	15.2	25.0	9.7	96.3
C019	465	10.7	39.7	21.6	24.7	14.0	96.7
C023	450	1.6	50.9	16.5	21.3	11.3	98.3
C024	450	4.0	47.4	16.9	25.5	10.2	97.9
C025	450	1.3	50.0	15.6	23.0	11.4	98.6

externally heated by electric elements surrounding the reactor chamber.

At the beginning of a run, a batch of wood chips was fed into a hopper sitting of top of the reactor. The maximum holding capacity of the hopper was 250 kg or air-dry biomass. The hopper was equipped with a screw at the bottom and was hermetically sealed. The maximum throughput of material from the hopper to the reactor was 25 kg h^{-1} for the experiments herein reported. The average residence time of the gas and vapour phase products in the reactor was empirically determined to be about 40 s (1).

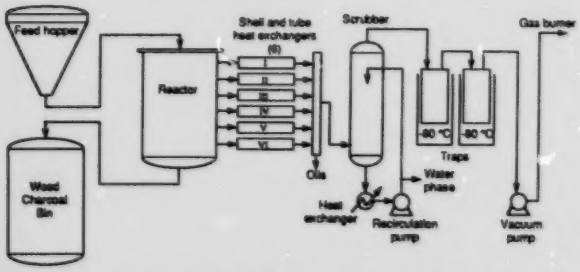

Figure 1: Schematic of the vacuum pyrolysis process development unit

The heating plate temperatures increased from top to bottom of the reactor. A typical temperature profile was 200°C to 450°C. The radial temperature gradient for any heating plate was lower than 5°C during a normal run. The system was operated below 10.7 kPa absolute. Air leakage through the system was negligeable.

Cooling and recovery of the pyrolysis vapour products was performed through a series of three condensing systems. The Primary Condensing Unit (P.C.U.) was composed of a series of six shell and tube heat exchangers set in parallel near the six reactor outlets. Those heat exchangers have been labeled I to VI in Figure 1. The largest portion of the pyrolysis oils was recovered in the P.C.U. The Secondary Condensing Unit (S.C.U.) consisted of a scrubber whose objective was to condense the steam generated during pyrolysis. The Tertiary Condensing Unit (T.C.U.) comprised a series of cold traps for the protection of the mechanical pump.

Wood charcoal produced was continuously removed from the reactor chamber through a screw conveyor and was discharged into a tank after being cooled down. The noncondensable gases were analysed by gas chromatography and their volumetric flowrate was recorded before they were flared.

Runs C010, C012 and C014 were performed with *Populus euramericana*, clone I-45/51, provided by Forintek Canada Inc. (Ottawa, Ont.). Runs C015 to C025 used *Populus deltoïdes* as feedstock, clone D-38, also provided by Forintek. The two samples were essentially all sapwood with no bark. It was supplied to our laboratory in the form of wood chips (1/4" - 1/2" Tyler sieves). Moisture content of the air-dry feedstock varied between 5 and 7% and the average ash content was 0.6%.

Runs # D003 to D009 were performed with a mixture of shredded forestry wastes composed of spruce (60%) and bark (40%) kindly provided by Biosyn in St-Juste-de-Bretenières, Province of Quebec. The biomass had been air-dried in the rotary kiln before shipment to our laboratory. The ash content of this material was 1.89%.

RESULTS

The two main objectives of the Process Development Unit were (i) to assess the vacuum pyrolysis concept using a multiple hearth furnace fed with biomass at throughputs of up to 25 kg h^{-1} and (ii)

Table 2 Variation of Heat of Pyrolysis With Pressure

RUN	REACTOR TEMPERATURE (°C)	REACTOR PRESSURE (kPa)	CONVERSION (%)	ΔH_r ($kJ \cdot kg^{-1}$ dry wood feedstock)	ΔH_r ($kJ \cdot kg^{-1}$ of wood converted)
C019	465	10.7	75.3	450	600
C023	450	1.6	78.7	570	720
C024	450	4.0	74.5	550	730
C025	450	1.3	77.1	560	730

to make a preliminary feasibility study of the process. Problems such as the heat transfer limitation in the reactor and the mass and energy balances have also been addressed during the study.

Yields and mass balance

Results for the operation of the P.D.U. under various final thermal decomposition temperatures and reactor pressures are presented in Table 1 of the paper. Experiments C010 to C025 were conducted with *P. deltoïdes* wood chips fed at a mass flowrate which varied between 0.8 and 4 kg h^{-1}. Oil, charcoal, pyrolytic water and gas yields are presented in Table 1 along with the mass balance calculation for each run. Table 1 indicates that the largest amount of oil was produced at the lower pressure conditions. The oil yield rapidly dropped however with even a slight increase in pressure. Table 1 also indicates that an outlet *reactor temperature* of 425-450°C is enough to maximize the oil production.

The mass balance calculations gave satisfactory results as observed in Table 1. Experiments D007 to D009 which will be described below were performed at flowrates four times higher than the C010-C025 runs. Unfortunately no mass balance calculation is available at this time to further confirm the observed product distribution when the P.D.U. was operated at higher throughputs.

Heat of pyrolysis

An important engineering parameter to be considered when designing a full scale pyrolysis plant is the quantity of energy required for the pyrolysis reactions. This value has been empirically determined using the P.D.U. described in this paper, and the detailed procedure has been published elsewhere (2).

The quantity of heat required to decompose wood (ΔH_r) will depend on the operating conditions used and the extent of reaction which has been reached. Under normal carbonization conditions, the reactions are exothermic. Under vacuum, the reactions were found to be overall endothermic as illustrated in Table 2 of the paper. We concluded that the secondary reactions (*e.g.*, thermal and catalytic cracking, repolymerisation, recondensation, oxidation and reduction reactions) which occurred under higher pressure conditions, released heat and hence contributed to the overall exothermicity. This was also differently illustrated in Table 2 where ΔH_r for run C019 at 10.7 kPa was less endothermic than ΔH_r for reactions C023, C024 and C025 which have been conducted at identical temperature but under a lower pressure.

Several D.T.A. and D.S.C. studies reported that the initial stage of thermal decomposition of wood is endothermic (3-6). In other words, ΔH_r varied with the extent of wood conversion. In Table 2, the ΔH_r calculations have been alternatively reported on the percentage of wood converted, as well as on an as-received anhydrous wood basis. % conversion was defined as:

$$\frac{\text{Mass of (oils + reaction water + gas)}}{\text{Initial mass of organic wood feedstock}} \times 100$$

As a result, we concluded that the heat required for vacuum pyrolysis of wood between 1.3 and 4.0 kPa was approximately 723 kJ per kg of organic wood converted. Overall, the reaction is slightly endothermic.

Heat transfer in the reactor

The main limitation in wood pyrolysis reaction is the rate of heat transfer in the reactor. The major capital cost item being the reactor, it is imperative not to overdesign this equipment. A study was undertaken to investigate the relative contribution of conduction and radiation as a mode of heat transfer in the multiple hearth furnace equipment described before. The heat transfer phenomena in a vacuum pyrolysis reactor for the treatment of scrap tires have been theoritically and empirically studied. The temperature for each of the six heating plates, the temperature variation along the furnace wall and the total electric power provided to the reactor were continuously recorded as a function of time during a run. The chemical and physical properties of the feedstock material, especially the thermal properties of rubber, widely varied with increasing decomposition temperature. These properties were investigated using a bench scale batch vacuum pyrolysis test unit.

A mathematical model was built which involved a series of differential heat transfer equations considering radiation and conduction, together with a

set of equations involving the material balance equations, the rubber devolatilization curve and the physicochemical modification of rubber. The model was found to favorably predict the overall heat exchange in the reactor. The detailed results will be reported elsewhere.

So far, the study showed that (i), the temperature distribution in the moving bed of rubber particles isn't uniform, and the heat exchange in the bed itself is mainly by conduction (app. 65% of the heat exchange), (ii) the heat transfer between the flowing rubber material and the furnace itself is mainly through radiation (app. 90%) and (iii) the chemical reaction is overall endothermal, with one small exothermal phase during the conversion process. Work is progressing with the objective to use the model for the design and optimization of vacuum pyrolysis systems.

Product properties and uses

The two main products obtained during vacuum pyrolysis of wood are pyrolysis oils and wood charcoal. Their general properties are summarized in Table 3 of the paper. It can be observed in Table 3 that the gross calorific value of both charcoal and oils is higher than the raw biomass material. Wood oils were found to be not corrosive for carbon steel at ambiant temperature and low acid and low water concentrations (7). The gas has a low heating value (6950 J g^{-1}) but is burnable.

Table 3 General Characteristics of Pyrolysis Oils and Charcoal

	OILS	CHARCOAL
Water content (%)	4.4	< 1
Gross calorific value ($kJ \cdot kg^{-1}$, anhydrous basis)	22,500	32,000
Elemental analysis (%)		
C	55.6	84.4
H	5.8	3.5
N	0.7	0.2
S	0.6	0.8
O (by diff.)	37.3	11.1
Proximate analysis (%)		
Ash	0.13	2.8
Volatile matter		18.5
Fixed carbon		78.7

Pyrolysis oils can be used as a liquid fuel or, alternatively, they can be upgraded in high grade motor fuel such as gasoline by simultaneous dehydration and decarboxylation over H-ZSM5 zeolite catalysts (8-10). An alternate and attractive route involves the extraction, the separation and the purification of commodity and fine chemicals which are found in biomass pyrolysis oils (8, 11-13). These were mainly mono- or diphenolic types and oxygenated heterocyclic compounds. Some of these compounds have pharmaceutical applications (*e.g.* phenols, eugenol and guaiacol) which have been found in significant amounts. Several other compounds such as methylcyclopentenolone, hydroxymethyl pyrone, vanillin, isoeugenol and diacetyl find application in the food industry as flavoring agents. Oxygenated heterocyclic compounds such as furfural, furfuryl alcohol and butyrolactone have special use in paint industries. Recently we have identified several other compounds with a fairly high market value such as coniferyl alcohol and coniferaldehyde.

CONCLUSIONS

A multiple hearth reactor has been successfully tested for the production of high yields of liquid fuels and chemicals. Biooil yields reached about 50% by weight of the air-dry feedstock under the lower pressure conditions used (2 kPa). Both the oil and charcoal have higher calorific value than the raw wood feedstock. Heat required for the pyrolysis of wood is slightly endothermic and was determined to be approximately 725 kJ kg^{-1} of organic wood converted. Heat is mainly transferred by radiation in the type of reactor used.

One promising and short term application of the process is scrap tires. A pilot plant unit has been built and tested. Continuous feeding of rubber chunks under a vacuo in the system has been successfully achieved. Work is progressing to scale up the process to the 1000 kg h^{-1} throughput capacity.

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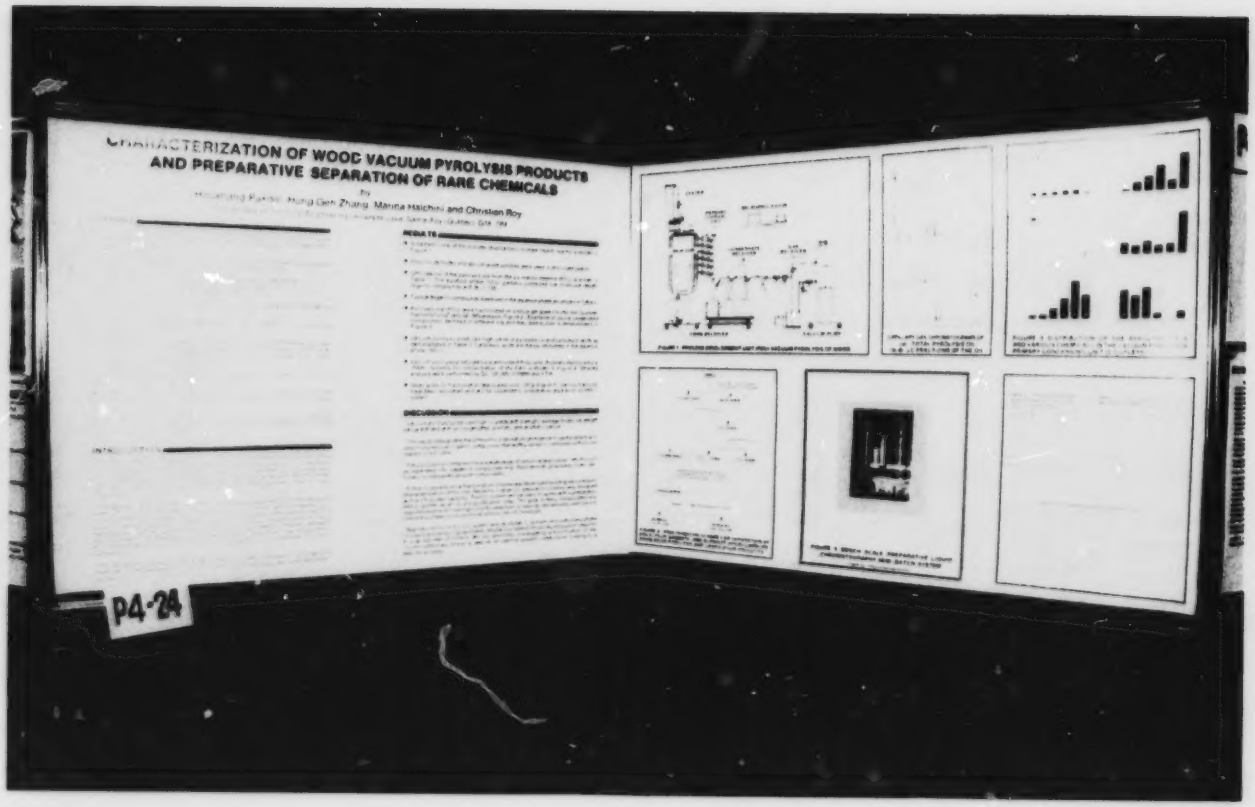
CHARACTERIZATION OF WOOD VACUUM PYROLYSIS PRODUCTS
AND PREPARATIVE SEPARATION OF RARE CHEMICALS
by
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CHARACTERIZATION OF WOOD VACUUM PYROLYSIS PRODUCTS AND PREPARATIVE SEPARATION OF RARE CHEMICALS

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A qualitative and quantitative characterization of organic liquids from vacuum pyrolysis of wood has been conducted using GC, GC-MS, GC-FTIR and FTNMR spectroscopic techniques. The major pyrolysis products were low molecular weight carboxylic acids and sugars. Pyrolysis oils were first sub-fractionated on a small liquid chromatographic column with 1 g capacity into various fractions. The results showed a wide variation in characteristics of the oils recovered at different outlets of the reactor. The value of these oils has been investigated as a source of commodity and rare chemicals. A separation method was developed to analyse the aromatic hydrocarbon content of both organic and aqueous phases and their environmental and toxicological impact was discussed. Decomposition of wood component was also studied applying Diffuse Reflectance Infrared Fourier Transform spectroscopic technique (DRIFT) on the solid residues. A series of equations were developed to calculate Klason residue, as well as glucose and xylose content of the solid residues. Small scale sub-fractionation of the pyrolysis oils was recently scaled up to 100 g. The large column was designed to prefractionate the wood pyrolysis oil into various groups, ideally as an oil purification step prior to preparative separation on HPLC system.

On a caractérisé sur le plan qualitatif et quantitatif les liquides organiques obtenus lors de la pyrolyse sous vide du bois, à l'aide des techniques de CG, CG-SM, CG-IRTF, et de techniques spectroscopiques IRTF et RMN-TF. Les principaux produits de la pyrolyse étaient des acides carboxyliques et des sucres de faible masse moléculaire. Les huiles pyrolytiques ont d'abord été fractionnées sur une petite colonne chromatographique (capacité de 1 g). Les résultats ont mis en évidence des variations importantes dans les caractéristiques des huiles récupérées aux différents points de sortie du réacteur. On a étudié la valeur de ces huiles en tant que source de produits de base et de produits chimiques rares. Une méthode de séparation a été mise au point pour déterminer la teneur en hydrocarbures aromatiques de la phase organique et de la phase aqueuse et leur impact environnemental et toxicologique a été discuté. On a également étudié la décomposition du bois en appliquant la technique de spectroscopie infrarouge à réflectance diffuse et à transformée de Fourier (DRIFT) aux résidus solides. Une série d'équations ont été élaborées pour calculer le résidu de Klason ainsi que la teneur en glucose et en xylose des résidus solides. Le fractionnement des huiles pyrolytiques a récemment été mis à l'échelle pour une quantité s'élevant à 100 g. La grande colonne utilisée à cette fin a été conçue pour pré-fractionner l'huile pyrolytique du bois en divers groupe, idéalement pour purifier l'huile avant sa séparation préparative sur système CLHP.

INTRODUCTION

Significant quantities of lignocellulosic residues are generated annually by the forest industries *e.g.* pulp and paper. Bark as an example of wood constituent, has very limited application and is being accumulated every year. Biomass as a general term, can be converted into different types of fuels and chemical feedstocks by a variety of thermochemical processes. Depending on the conversion process and biomass constituents, oil composition changes considerably and usually reflects the reactor environment (1). Nevertheless liquefaction processes can be designed with desirable characteristics.

Carbonization and pyrolysis are applied for transformation of wood into solid fuels. The conventional carbonization technique is an old technique with less efficiency. The pyroligneous liquid produced by carbonization has certain commercial value but the technology is presently unable to meet the requirements of the fine chemicals production. The ATOCHEM plant located in Premery, France, is a wood carbonization technology plant for production of 20 000 t/year of charcoal (2). The generated pyroligneous liquors are subjected to various distillation processes in series, for production of various fine chemicals e.g. diacetyl as butter

flavor, methyl cyclopentenolone as caramel flavor and oxymethyl pyrone as strawberry flavor. In Brazil, demand for acetic acid, ethyl acetate and methanol is steadily growing (3). This has therefore encouraged their large wood carbonization industry with 7.5 x 10^6 t/year of wood charcoal (produced in 1986) to investigate the possible recovery of the more volatile products of wood decomposition liquid product. They have calculated that the return of investment for a 40 tons of charcoal per day plant could be increased from 6 to 29% if acetic acid and methanol could be recovered and sold as by-products along with charcoal. Vacuum pyrolysis on the other hand is a new liquefaction technology and produces high yield of oil and a relatively good quality wood charcoal as solid residue.

The production of chemicals from biomass is a very important goal for the biomass thermochemical conversion industries. The objective of this investigation is the exploration of a new technology for economical application of biomass vacuum pyrolysis oils. Detailed characterization of the pyrolysis oils is particularly important for their further reprocessing. This paper reviews our recent findings on pyrolysis, product characterization and large scale fractionation of the pyrolysis oils.

VACUUM PYROLYSIS

A vacuum pyrolysis Process Development Unit (PDU) of wood chips was developed recently in our laboratory and yielded approximately 50% oil, 20% solid residue, 20% water and 10% gas (4). The liquid products (oil and water) were collected in two different condensation units (Figure 1). The oil phase was collected in the Primary Condensing Unit (PCU) which consisted of six heat exchangers installed parallel in the six reactor outlets (H-I to H-VI respectively from top to bottom of the reactor). Aqueous phase on the other hand was collected in a series of cooling traps called Secondary Condensing Unit (SCU). The solid residue was collected at the bottom of the reactor and the pyrolysis gases were collected in metallic vessels.

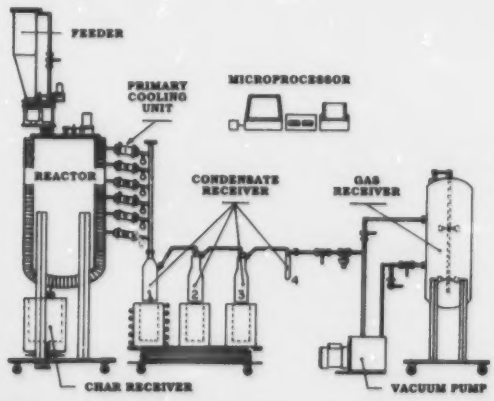

FIGURE 1: PROCESS DEVELOPMENT UNIT (PDU) VACUUM PYROLYSIS OF WOOD

PYROLYSIS PRODUCT CHARACTERIZATION

Carboxylic acids

Vacuum pyrolysis produced high yield of carboxylic acids (mainly formic and acetic acids). Depending on the pyrolysis conditions and the condensation system used, a large portion of formic and acetic acids were recovered in the SCU (Table 1). Quantitative gas chromatographic analysis method of the low molecular weight carboxylic acids was developed recently (5) in our laboratory and enabled us to measure the acids directly in both oil and aqueous phases.

Table 1: Pyrolysis conditions used and yields

Experiment No	Condensation Temperature Range (°C)	Pressure (mm Hg)	Oil yield[a]		Oil yield[b]		Acid Yield (C_1 to C_4)[a]	
			PSU	SCU	PSU	SCU	PSU	SCU
1	50-55	12	23.3	26.6	1.0	20.1	1.4	7.5
2	30-35	30	27.5	18.8	1.0	20.4	2.0	6.2
3	15-20	10	33.6	15.7	2.2	18.1	3.2	5.8

[a] Moisture and ash-free wood basis
[b] As-received wood basis
PCU = Primary Condensing Unit (condensers I-VI)
SCU = Secondary Condensing Unit (traps 1-3)

Liquid chromatographic Analysis

The pyrolysis oils which were recovered from the six reactor outlets (PCU) showed a wide difference in their composition (6). Gel permeation chromatographic analysis (GPC) of the six oils showed a weight-average molecular weight ($\bar{M}_w$) of 342, 528, 572, 393, 23 and 123 respectively from top to bottom of the reactor (H-I to VI). The GPC test for the aqueous phase showed $\bar{M}_w \leq 100$. The high molecular weight compounds with $\bar{M}_w > 300$ represented approximately 25% of the total pyrolysis oil.

Direct analysis of the pyrolysis oils obtained by various techniques are reported in the literature (7-8) but suffer from several drawbacks, in particular the quantitative analysis. However to our knowledge, there are only two general methods reported to be utilized for fractionation of the pyrolysis oils into various chemical classes including solvent extraction method (9) and the chemical adsorption method (10). The former technique was found rather long and tedious and quite often the phase separation is difficult due to the emulsion formation. In addition the yield of extraction depends on the solvent volume and extraction repetition number. High performance liquid chromatography technology on the other hand has recently reached a revolutionary stage, particularly in the pharmaceutical industry for large scale preparative separations. Liquid solid chromatography was found therefore a method of choice for preliminary fractionation and characterization of vacuum pyrolysis oils at the first stage, to be followed by preparative large scale separation of rare chemicals, as an example, which are in increasing demand (11).

1 g of the PCU oil was fractionated on 12.5 g silica-gel (60-120 mesh) into fourteen fractions by

increasing their polarity from F1 to F14. F1-F2 were found to contain mainly hydrocarbons and contributed between 0.15-1.5% of the PCU oils. F3-F11 contributed between 22-23% of the PCU oils. Their gas chromatograms showed appreciably better resolution compared to the initial oil (before fractionation). These fractions are particularly valuable and could be considered as quality index for various oils. High complexity of the pyrolysis oil results in low quantitative accuracy and less unambigeous assignments. Figure 2 demonstrates the distribution of pyrolysis oil and water (Fig. 2a) and examples of the typical compounds identified in F3-F11 (Fig. 2b-f). Histograms demonstrate in addition the distribution of various compounds concentrated and recovered in various reactor hearths. F12 contained a mixture of relatively polar compounds (29-36% of the PCU oil) compared to the F3-11. Its chromatogram however suffered from low resolution. F13 contained mainly high polar compounds including sugars and acids and contributed for about 26 to 30% of the PCU oils. Hydrolysis of this fraction produced about 3 to 14% sugars, mainly glucose. F14 was found to contain only 1-3% of the PCU oil with mainly polymeric and highly polar compounds.

The aqueous phase was distilled and the distillate was analysed by GC and GC-FTIR techniques. Table 2 presents typical chemical compounds which were identified. They are mainly low molecular weight and water soluble compounds. Their high water solubility renders low separation efficiency. Nevertheless satisfactory results were obtained by direct GC-FTIR analysis of the aqueous phase on "Durabond" carbowax capillary column. Water troubled some by giving rise to a broad signal which may have masked coeluting peaks.

Table 2: Typical organic compounds identified in the aqueous phase (SCU)

Formic acid	2-Butanone
Acetic acid	Methanol
Acetaldehyde	Dimethylglyoxal
Methylformate	Crotonaldehyde
Propanal	1-Hydroxy-2-Propanone
Acetone	Furfural
Methylacetate	

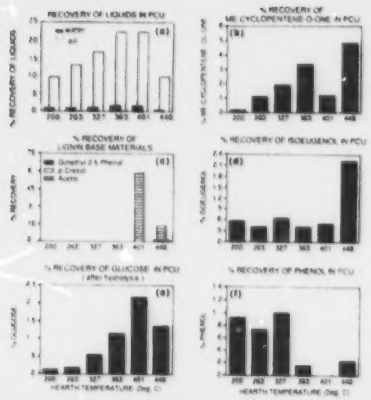

FIGURE 2: DISTRIBUTION OF THE PYROLYSIS OILS AND VARIOUS CHEMICALS IN THE VACUUM PYROLYSIS PRIMARY CONDENSING UNIT (6 OUTLETS)

Large scale liquid-chromatography

Following a method development on a small column with 1 g capacity, a large column with 100 g capacity and 80 ml min^{-1} flow rate was designed. The oil (≈ 20% H_2O content) was fractionated on 1500 g silica-gel (60-120 mesh with app. 4-5% moisture content) into six major classes eluting subsequently with 10% CH_2Cl_2 in petroleum ether, 40% and 70% CH_2Cl_2 in petroleum ether, 100% CH_2Cl_2, ethylacetate and 10% formic acid in methanol. All the fractions were then vacuum distilled to recover the solvents. The silica-gel was regenerated at 400°C in furnace for recycling. Satisfactory mass balance (≥ 95%) and separation reproducibility was obtained. Groups 2-4 identified as the most valuable mixtures contributed to about 40% of the dry oil basis. Yield and composition of the groups 2-5 varied from one feedstock to another. Presently further investigations are in progress for optimization of the column performance. The large column fractionation was designed as a clean up step for preparative separation of pure compounds on a high performance liquid chromatography system which will be installed on line with LC and pyrolysis system.

Characterization of the vacuum pyrolysis solid residue

Chemical analysis of chars produced at 200, 263, 327, 363, 401 and 448°C in a Process Development Unit was performed by means of wet chemistry together with chromatography and Diffuse Reflectance Infrared Fourier Transform technique (DRIFT). Residual polysaccharides of the pyrolysis solid residues were hydrolysed in trifluoroacetic acid (TFA). TFA soluble fraction, mainly glucose and xylose, were measured by GC. TFA insoluble fraction is designated as the Klason residue which is reffered to the unconverted lignin or produced by recondensation reactions during pyrolysis. The regression equations as function of possible combinations of intensity rations of the twelve IR

bands between 1595 and 895 cm^{-1} against Klason residue and glucose and xylose values of the initial wood sample and the six pyrolysis solid residues together with available published data (12) were developed (see ref. 13 for detail). A good correlation between Klason residue content calculated from the regression equation and conventional analysis were obtained for a number of samples from vacuum pyrolysis. Coal-like samples with less than 10% glucose and 3% xylose, on the other hand, exhibited a non linear correlation. This study demonstrated the usefulness of the DRIFT technique, as a fast technique to predict Klason residue and residual sugars of a wide range of solid samples with wood-like nature. The technique was found very rapid compared to the tedious wet chemistry approach. Degradation, decomposition and recondensation reaction proceeds as the reactor hearth temperature increases. Ultimately coal like nature prevails as the bed temperature exceeded 327°C.

Environmental aspects

Polycyclic aromatic hydrocarbons (PAH), benzo-a-pyrene in particular, are ubiquitous environmental pollutants and are formed from both natural and anthropogenic sources. Wood gasifier is an example of anthropogenic source which produces mainly PAH as a by-product. We have recently developed a separation method to analyse the aromatic and aliphatic hydrocarbon content of both wood vacuum pyrolysis oil and aqueous phases (14). Hydrocarbon distribution was found to be strongly dependent on the reactor bed temperature. Aromatic hydrocarbons contributed between 0.06 to 0.24% of the pyrolysis organic phase (H-I to H-VI oils). Aqueous phase contained only a trace quantity of aromatic hydrocarbons. Gas chromatographic analysis of the aromatic fraction was made. FT-NMR spectroscopy further enabled us to determine the hydrocarbon type distribution of the aromatic hydrocarbon fractions and showed approximately 47 to 58% aliphatic side chain hydrogens. Such a high aliphatic hydrogen content indicates the highly branched nature of the aromatic hydrocarbons as confirmed further by FT-IR analysis technique. Highly branched chain PAH have not been reported to have significant mutagenic activity. We therefore concluded that both the vacuum pyrolysis oil and the aqueous phases have no environmental impact unless they are accumulated and concentrated in hydrocarbon fractions.

CONCLUSION

- Vacuum pyrolysis of wood in a process development multiple hearth furnace produced an organic liquid phase (50% by wt.), wood charcoal (20%) gas (10%) and an aqueous phase (20%).

- Qualitative and quantitative analysis of the organic phase showed a wide variation in the quality of the oils recovered at the six reactor outlets.

- GPC analysis of both the organic and aqueous phases showed that:

  $100 < \bar{M}_w$ (organic phase) < 600
  $\bar{M}_w$ (aqueous phase) ≤ 100

- Prefractionation of pyrolysis oil was found to be a crucial step prior to GC or GC/MS analysis.

- A small scale LC system enabled us to fractionate the pyrolysis oils into various cuts with their order of polarity.

- Vacuum pyrolysis yielded approximately 9% by weight (moisture and ash-free wood basis) of low molecular weight carboxylic acids, mainly formic and acetic. The low molecular weight acid content in the organic phase (P.C.U.) and the aqueous phase (S.C.U.) were 1.5% and 7.5% respectively.

- A PAH analysis procedure for both the aqueous and the organic phases was developed. It showed no significant environmental and toxicological impact.

- A Diffuse Reflectance Infrared Fourier Transform spectroscopic technique (DRIFT) was successfully applied to characterize the pyrolysis solid residues (wood charcoal).

ACKNOWLEDGMENT

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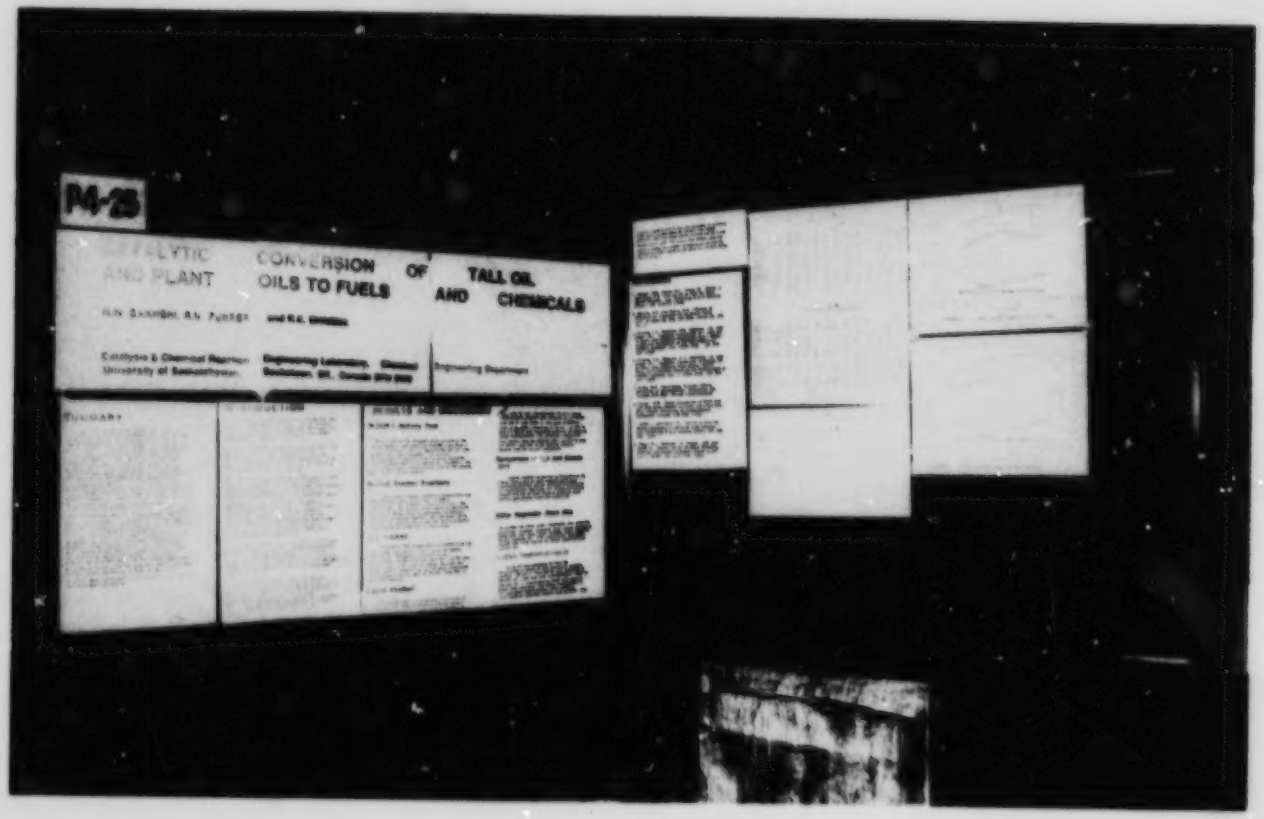
P4-25
CONVERSION OF
OILS TO FUELS
TALL OIL
AND CHEMICALS

CATALYTIC CONVERSION OF TALL OIL AND PLANT OILS TO FUELS AND CHEMICALS

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As conventional energy sources deplete, the need for developing alternative energy sources becomes imperative. In recent years, biomass derived oils (such as vegetable/plant oils, tall oil and biomass-tars) are attracting increasing attention as alternative sources of fuels and chemicals. These are all renewable sources. Various routes (such as combustion, liquefaction, fermentation to ethanol, etc.) have been tried for the utilization of biomass. Another interesting route is the direct upgrading of variously-derived bio-oils and plant/vegetable oils to clean premium quality transportation fuels and chemicals by using shape selective zeolite catalysts such as Mobil's ZSM-5 Catalyst.

We have studied the direct catalytic conversion of a variety of plant oils (such as flax, sunflower, canola, etc.) and depitched tall oil (derived from the soap skimmings recovered from the black liquor left behind in Kraft pulping operations) to chemicals and gasoline range hydrocarbons using H-ZSM-5 catalyst. The studies were carried out in a microreactor at atmospheric pressure and conversions were high (70-90%). The gas product mostly consisted of C_2-C_4 paraffins and the liquid product mostly consisted of aromatic hydrocarbons in the C_6 - C_9 range. In most cases, coke formed was small and the catalyst could be regenerated easily (1 h at 600°C). In addition to the above information, we also plan to present results on the upgrading of biomass derived oils using HZSM-5 and other catalysts.

Au fur et a' measure que s'epuisent les sources d'energie traditionnelles, le besoin de mettre au point des sources d'energie de remplacement devient imperatif. Depuis quelques annees, les huiles derivees de la biomasse (comme les huiles vegetales, le tallol et les goudrons biomassiques) retiennent de plus en plus l'attention en tant qu'autres sources possibles de combustibles et de produits chimiques. Il s'agit dans tous les cas de sources d'energie renouvelable. On a essaye d'utiliser la biomasse de diverses facons (par ex., combustion, liquefaction, fermentation pour former de l'ethanol, etc.). Une autre utilisation interessante est l'amelioration directe de bio-huiles de diverses sources et d'huiles vegetales pour en faire des carburants pour le transport et des produits chimiques de haute qualite' en utilisant des catalyseurs de zeolite selectifs en fonction de la forme comme le catalyseur ZSM-5 de Mobil.

Nous avons etudie la transformation catalytique directe de diverses huiles vegetales (comme celles de lin, de tournesol, de canola, etc.) et du tallol exempt de brai (provenant des ecumages de savon recuperes a partir de la liqueur noire produite par les operations de preparation de la pate draft) en produits chimiques et en hydrocarbures de type essence au moyen du catalyseur H-ZSM-5. Les travaux ont ete effectues dans un microreacteur a la pression atmospherique et a une temperature variant de 370 a 520°C. Dans la plupart des cas, le taux de conversion etait eleve (70-90%). Le produit gazeux etait principalement constitue de paraffines en C2-C4 et le produit liquide etait principalement constitue d'hydrocarbures aromatiques dans la gamme C6-C9. Dans la plupart des cas, il se formait peu de coke et le catalyseur pouvait facilement etre regenere (1 h a 600° C).

En plus de l'information susmentionnee, nous avons aussi l'intention de presenter les resultats relatifs a l'amelioration des huiles obtenues a partir de la biomasse, au moyen du catalyseur HZSM-5 et d'autres catalyseurs.

The products consisted of three main fractions: a gaseous fraction (mostly consisting of C_1 to C_5 hydrocarbons and CO), a liquid fraction (primarily consisted of the gasoline range hydrocarbons) and coke (carbonaceous deposits left on the catalyst). The scheme for product collection and separation is shown in Fig. 1.

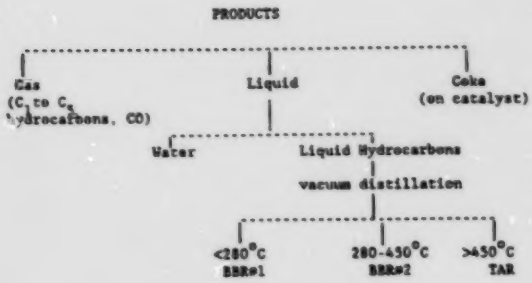

Figure 1 Product collection Scheme.

RESULTS AND DISCUSSION

H-ZSM-5 Activity Test

Blank runs using chipped glass sieved to the same particle size used for H-ZSM-5 resulted in low conversions (15%) of depitched tall oil. Gas production was negligible. The various hydrocarbons fractions in the product probably resulted from thermal cracking [3]. Therefore, the high conversions obtained were due to the activity of H-ZSM-5 zeolite catalyst.

Overall Product Fractions

The overall product fractions obtained during the catalytic runs at 2.6 and 5.8 WHSV, respectively, are plotted in Figures 2 and 3. As can be seen, the tall oil conversions ranged from 71 to 93% depending on the operating conditions. The time-on-stream duration was between 30 to 132 min. A mass balance over the entire process indicated better than 94% in each case.

Gas Product

Increasing the temperature increased C_1 to C_4 selectivity from 49 to 77 wt.% at an oil space velocity 2.6. Propylene was the largest component, comprising upto 38.4 wt.% of the gas product at 519°C and 5.8 WHSV. Overall, the olefin/paraffin ratio in the gas product increased with temperature as well as WHSV. (See Ref. 6 for more details).

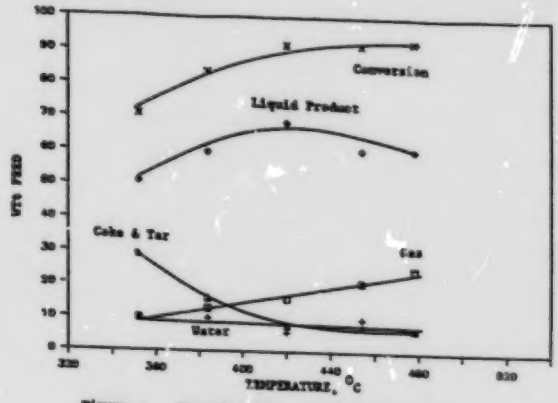

Figure 2 Overall product composition, 2.6 WHSV.

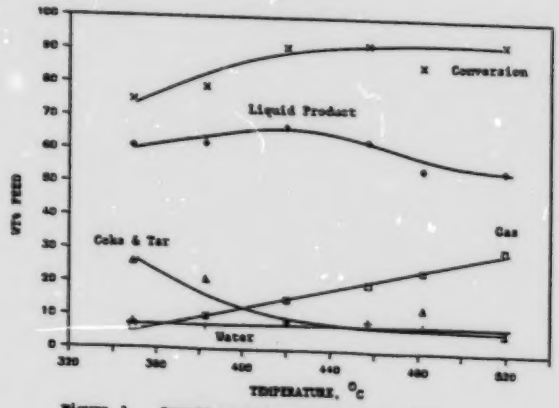

Figure 3 Overall product composition, 5.8 WHSV.

Liquid Product

The liquid hydrocarbon product consisted of three fractions distinguished by boiling ranges: <280°C (BBR #1), 280-450°C (BBR #2) and >450°C (tar). A maximum of 70 wt.% liquid hydrocarbons product was obtained at 2.6 WHSV and 420°C (see Table 2). The yield of BBR #1 fraction reached a maximum of 39 wt.% at 478°C and 2.6 WHSV and consisted primarily of gasoline range hydrocarbons. The aromatic content of this fraction was the highest (84 wt.%) at 478°C and 2.6 WHSV [see Ref. 6 for details]. Usually, toluene was the largest component.

Comparison of Tall and Canola Oils

Earlier studies conducted by Prasad et al [3] using canola oil as feed material have been compared with the results obtained from the tall oil experiments. Basically the results are similar except that tall oil feed tends to produce more olefinic gas product than the Canola oil.

INTRODUCTION

As conventional energy sources deplete, the need for developing alternative energy sources becomes more and more important. Biomass oils (including plant and vegetable oils) have been suggested as one such alternative.

Efforts to operate direct injection engines using vegetable oils has had limited success [1]. Difficulties arise due to the high viscosity of the vegetable oils. Attempts at reducing the viscosity via blending with diesel fuel or the preparation of the less viscous methyl ester has also resulted in a number of inherent difficulties [2].

Earlier work [3,4] carried out at the Catalysis and Chemical Reaction Engineering Laboratory (CCREL), University of Saskatchewan, has shown that Canola oil can be converted directly to gasoline range hydrocarbons using HZSM-5 as a catalyst (@ 1 atm and 370-400°C temp.). Saskatchewan Research Council (SRC) has also shown that Canola oil can be converted to specification diesel fuel products using the conventional refining technology [5]. Additional work at CCREL has shown that a variety of vegetable oils when treated with HZSM-5 yield gasoline range hydrocarbons [6].

Earlier attempts by Lewko and Secor [7] to use crude or depitched tall oil as a diesel replacement, met with unsatisfactory results. On the other hand, work carried out at CCREL has shown that depitched tall oil also can be reacted with HZSM-5 to yield gasoline range hydrocarbons and other chemicals [6].

In this paper, catalytic conversion results obtained from tall oil (a pulp mill byproduct) and a variety of vegetable oils will be compared and discussed. In addition, our recent results obtained for the conversion of a biomass derived oil (oil obtained from the liquefaction of wood) using HZSM-5 as a catalyst, will also be presented.

MATERIALS AND METHODS

Feed Material

Partially de-pitched tall oil (approximately 51% of the pitch was removed representing 20% of the total Crude tall oil volume) was obtained from the Prince Rupert pulp mill in British Columbia. Its composition is given in Table 1.

Experimental Procedure

A typical procedure for carrying out catalytic conversion experiments with HZSM-5 is described below.

TABLE 1
Comparison of Tall Oil and Canola Oil compositions.

	Canola oil	Crude Tall Oil
Resin acids	Wt%	Wt%
Abietic acid		20-25
Palustic acid		8-10
Neoabietic acid		22-27
Dihydroxyabietic acid		4-5
Isodextropimaric acid		3-4
Unknowns		29-43
Approximate range of resin acids:		22-45
Fatty acids		
Palmitic acids	4.3	
Stearic acids	1.9	
Oleic acid	60.5	46-48
Erucic acids	0.3	
Linoleic acids	22.7	43-45
Linolenic acids	8.0	1-2
saturated acids		6-8
other	2.3	
Approximate range of fatty acids:	100	28-52
Unsaponifiables		
Phytosterols		25-35
Alcohols		5-15
Hydrocarbons		33-40
Approximate range of unsaponifiables:		22-35

The values given in Table 1 represent typical values. However, due to the wide variability in tall oil compositions, they do not represent minimum values and consequently do not add up to 100.

De-pitched tall oil was passed over 1 g of H-ZSM-5 zeolite in a fixed bed micro-reactor. The micro-reactor was constructed of #316 ss tubing and was 9 mm in diameter and 0.51 m long. The undiluted H-ZSM-5 catalyst was loaded approximately mid way along the micro-reactor. Depitched tall oil was pumped into the microreactor using a syringe pump through a valve located directly above the micro-reactor. The flow diagram of the catalytic conversion apparatus is given in Ref. [6].

A typical run was carried out as follows: the micro-reactor was loaded with H-ZSM-5 catalyst and heated to the reaction temperature in a stream of argon (1 L/h). Once the temperature of the micro-reactor stabilized at the set point, the argon flow was shut off and the syringe pump started. the rate of gas production was monitored to estimate the time-on-stream. Run time was started when the first gas bubble appeared in the gas collector. The endpoint for each experimental run was assumed to occur when the rate of gas production became erratic or decreased significantly. At this point, the syringe pump was shut off. Products were then collected until no more gas eluted and the micro-reactor was allowed to cool in a stream of argon (approximately 10 mL/h).

TABLE 7
Detailed product composition (wt%).

RUN #	6	1	7	9	13	3	5	8	10	11	12	2	4
Temp., °C	352	384	420	454	478	349	383	420	457	482	519	400	399
WHSV, g oil/g cat./h	2.6	2.6	2.6	2.6	2.6	5.8	5.9	5.8	5.8	5.8	5.8	4.2	4.2
GAS PRODUCT													
C1-C4	5.7	8.3	11.2	14.4	19.0	3.1	5.9	10.5	16.1	17.6	23.8	8.8	9.0
C5's	1.0	1.4	1.4	1.4	2.0	0.4	0.8	1.2	1.7	1.8	2.2	1.1	1.1
CO	2.3	2.7	3.0	3.0	3.6	1.7	2.3	2.9	1.7	3.5	3.8	2.8	2.9
Total	9	12	16	19	25	5	9	15	19	23	30	13	13
LIQUID PRODUCT, BBR#1													
non-aromatics	7.3	11.1	8.2	8.4	6.3	8.1	11.5	9.1	9.8	8.5	6.2	12.4	12.0
aromatics	10.5	18.6	19.7	25.2	32.7	11.5	13.1	17.0	23.4	26.3	31.2	23.7	19.8
Total	18	30	28	34	39	20	25	26	33	35	37	36	32
LIQUID PRODUCT, BBR#2	34	31	42	29	23	42	38	41	30	21	18	32	36
WATER	10	10	6	10	7	8	7	9	9	8	8	7	8
COKE & TAR	29	16	9	9	7	26	21	9	8	14	7	13	12
TOTAL(wt% product)	100	100	100	100	100	100	100	100	100	100	100	100	100

Other Vegetable/Plant Oils

A number of other plant/vegetable oils (soybean, sunflower, linseed, mustard, high erucic acid rape seed and flax) have been studied using HZSM-5 as the catalyst [6]. The conversions and other results are quite similar to those obtained with canola oil.

Catalytic Treatment of a bio-oil

A bio-oil was produced [8] from the liquefaction of wood at high pressures (oxygen content - 20 wt.%). This bio-oil was treated with HZSM-5 at 1 atm and over a temperature range of 370°C-450°C in coprocessing mode with tetralin, steam and methanol. The major components in the upgraded liquid product were aromatic hydrocarbons, phenols, furans and alcohols. The results suggest that it may be possible to achieve high pitch conversions by using a two stage process: the first stage being carried out at a low temperature (- - 370°C) and a low WHSV and the second stage at a higher temperature of 410°C. Additional work needs to be done to confirm these observations.

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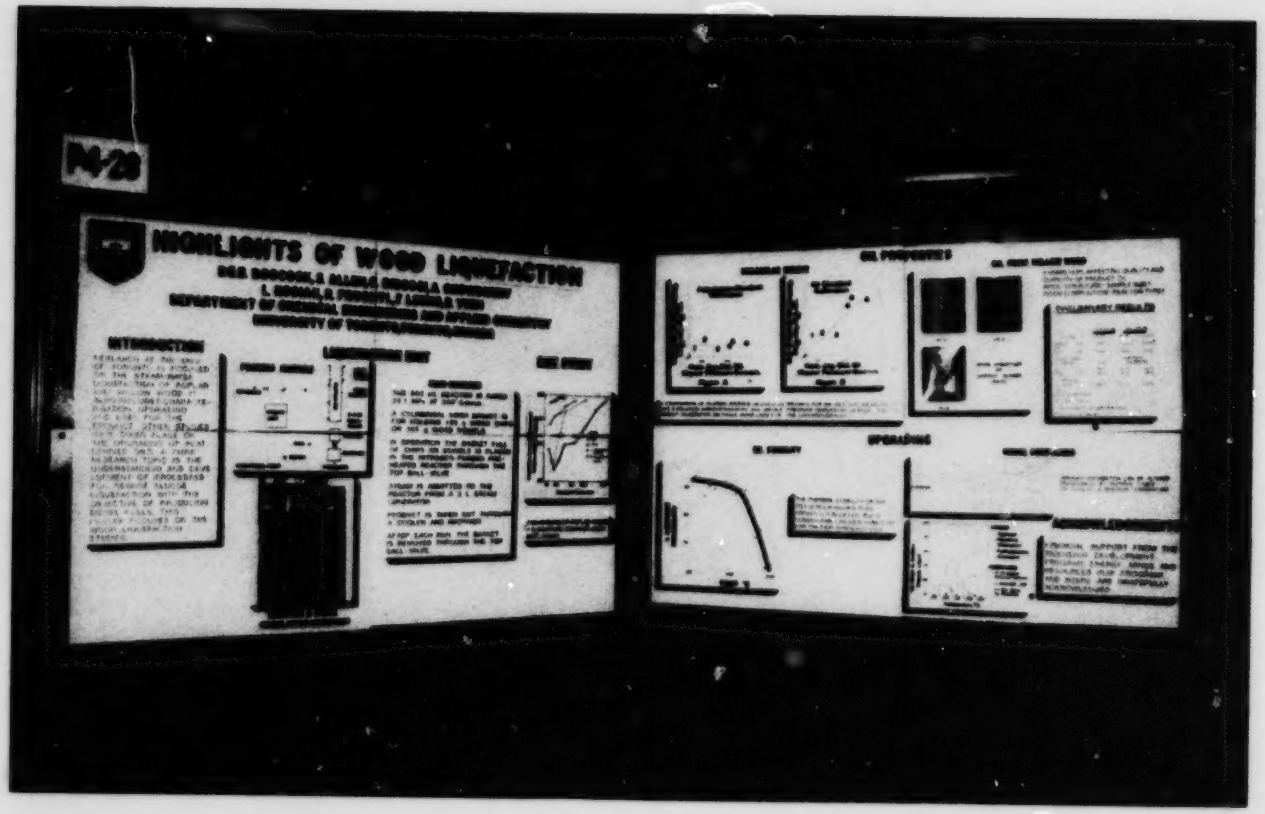
N-28
HIGHLIGHTS OF WOOD LIQUEFACTION
INTRODUCTION
OIL PROPERTIES
OPERATING

THE STEAM/WATER LIQUEFACTION OF POPLAR WOOD IN A GRAVITY FED REACTOR: a) THE EFFECT OF FEED SIZE AND b) UPGRADING OF WOOD OIL MODEL COMPOUNDS

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Liquefaction of non-powdered poplar wood by steam thermolysis has been conducted in a 600 mL cylindrical reactor. The feed in the form of chips, sticks, and up to 3 cm dowels was treated in the nitrogen-purged reactor with steam at 330-350°C for reaction times of 15-180 seconds. Reaction times of 45 s, 90 s, and 180 s were required for the complete conversion of chips, sticks and 3 cm diameter dowels respectively to oil, water, and gas products. Over 90% of the mass of chips, 70% of sticks, and 50% of dowels were converted to products in a reaction time of 15 s (conversion is based on recovered acetone-insoluble material). For feeds less than 2.5 cm diameter in size, an unexpected linear relationship between conversion and initial suface area/volume ratio was found when using steam at 350°C. Also when poplar chips (and dowels below about 1.3 cm diameter) were treated with 350°C steam, wood fragmentation was fast, as evidenced by a sudden release of finely divided material which became suspended in the aqueous phase.

The catalytic hydrodeoxygenation of wood oil model compounds such as phenol, anisole and guaiacol, demonstrated that sulfiding greatly increased the activity of $MoO_3/CoO/Al_2O_3$ catalysts such that temperatures some 100°C lower than those required for the unsulfided catalysts could be employed. By suitable selection of catalyst and temperature, products can be directed towards aromatics (benzene, toluene, xylene), cycloparaffins or phenols. The production of toluene/xylene mixtures with the exclusion of benzene could probably be accomplished by the addition of methanol.

On a réalisé la liquéfaction de bois de peuplier par thermolyse à la vapeur, à l'aide d'un réacteur cylindrique de 600 mL et d'un générateur de vapeur de 2 L. Le bois utilisé à cette fin, qui était constitué de copeaux, de bâtonnets et de chevilles pouvant atteindre 3 cm de diamètre, a été traité avec de la vapeur à 330-370°C pendant 15-180 secondes dans un réacteur purgé à l'azote. Il fallait 45, 90 et 180 secondes respectivement pour transformer complètement en huile, en eau et en produits gazeux les copeaux, les bâtonnets et les chevilles pouvant atteindre 3 cm de diamètre. Plus de 90% des copeaux, 70% des bâtonnets et 50% des chevilles étaient transformés en produits après 15 secondes (d'après la quantité de matière insoluble dans l'acétone qui a été récupérée). Dans le cas des morceaux possédant un diamètre inférieur à 2, 5 cm et traités avec de la vapeur à 350°C, il y a une relation linéaire entre la réaction de transformation et le rapport surface initiale/volume. De plus, lorsqu'on traite des copeaux de peuplier (et des cheville possédant un diamètre inférieur à environ 1, 3 cm) avec de la vapeur à 350°C, la fragmentation du bois procède rapidement, comme en témoigne la production soudaine de matière finement divisée qui entre en suspension dans la phase aqueuse.

INTRODUCTION

Studies of the direct conversion of wood chips to non-char products by high temperature steam treatment have been continued. These studies were an expansion of our previous work on the liquefaction of single wood chips using steam at high temperature and pressure (1). Approximately 99% of the feed material was converted to acetone-soluble oil, aqueous phase organics, and gas after 2 minutes reaction time. No catalyst or reducing gases were involved in the process. The oil yield was 40-45% and the water-free oil contained 70% carbon, 6% hydrogen, and 24% oxygen. The oils which have been produced so far, probably require upgrading. They have a high oxygen content, mostly in the form of phenolic and methoxy groups. They are also just solid at room temperature due to the presence of high molecular weight compounds. As such they have potential as adhesives.

EXPERIMENTAL ASPECTS

Although the liquefaction equipment, operation, material, and product separation have been described elsewhere (2), brief information is presented here for the convenience of the reader.

Equipment

The liquefaction unit consists of: a steam generator, a cylindrical 'cascade' reactor, reactor inlet and outlet ball-valves, a product let-down lock and cooler, and a product collector. The complete liquefaction unit is shown schematically (not to scale) in Figure 1.

The steam generator is a 2 L autoclave vessel capable of producing steam at 350°C, and employs upper and lower temperature control. The cascade reactor made of TP316 stainless steel has an internal diameter of 3.8 cm and an internal volume of 600 mL. There are three steam inlet ports, and three thermocouples and one pressure gauge monitor the internal conditions. The reactor is heated by two six feet long (1/8 inch O.D.) heaters (4 KW) joined in parallel. The ball-valves are used for the input and discharge of wood products. The air-operated inlet valve is a 3.8 cm ball-valve, rated at 24.8 MPa at 370°C. The discharge ball-valve is of 1.3 cm diameter and rated at 18.4 MPa at 370°C. The product cooler is a 316 stainless steel 300 mL unit (I.D. 5 cm, 15 cm long) and rated at 13.8 MPa at 370°C. The cooler is jacketed with low pressure steam to allow easy flow of oil into the product recovery unit.

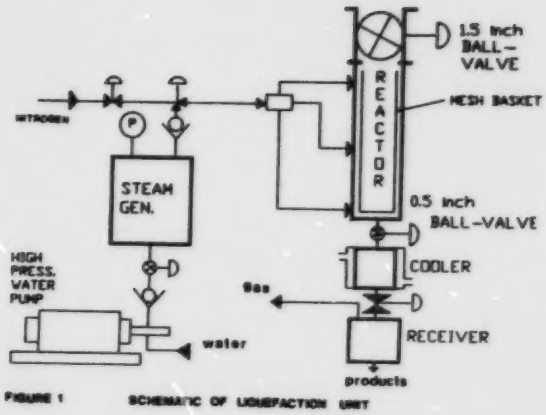

FIGURE 1 SCHEMATIC OF LIQUEFACTION UNIT

Operation

For a particular run, a cylindrical mesh basket containing chips or dowels or sticks was inserted into the nitrogen-purged preheated reactor. The reactor's inlet, outlet and vent valves were closed, and steam (330-350°C) was injected for a predetermined time (usually 7 s). After a period of reaction (15-180 s), the contents of the reactor were cooled in the product cooler and then discharged into the product receiver.

Materials

The feed material for liquefaction was poplar chips, dowels, and sticks. Wood chips, in the form of a standard IEA (2) feed material, were used for a part of the study. The dowels were made from sapwood of poplar clone DN38. The sticks were made from the irregular shaped cuttings of sapwood. The moisture content of the feed was 5-8% as used.

Product Separation

The major product was "acetone-soluble oil", which included oil obtained directly from the reactor, reactor wash oil and those aqueous-phase solids which were also acetone soluble. The other products were aqueous-phase liquid, acetone-insolubles (original wood and char), and gas. The acetone-free oil, on cooling, solidified and separated from the aqueous products. The aqueous products were centrifuged to recover aqueous phase solids. Products that were not discharged from the reactor were recovered by washing the unit with acetone. The acetone wash was then filtered, and the wash oil was recovered by evaporating the acetone in a Buchi Rotary evaporator at 60-70°C under vacuum. The remaining acetone and moisture were removed by keeping the oil under vacuum for 2-3 days.

DISCUSSION OF RESULTS

In the wood liquefaction study, the following three reaction conditions were maintained throughout: (1) Steam injection time of 7 s, (2) 1 L of water in the steam generator, and (3) use of poplar chips, dowels, and sticks as feed materials. It should be emphasised that "steam temperature" refers to the temperature in the steam generator.

Liquefactions of 2.5 cm diameter dowels were performed using reaction times of 60, 90, 120, 150, and 180 seconds. Partially reacted dowels which were removed from the reactor were swollen with water. When steam enters the reactor, part condenses on the cooler walls at the base; some condenses on the surface of the wood, and some penetrates and condenses inside the wood structure. The latter provides much of the heat required for liquefaction.

The sorbed water is not just a heat transfer medium, since it also swells the outer section of the dowel and helps the physical disintegration of the wood, the first step in the breakdown. Fragments break off and fall into the aqueous phase at the base of the reactor, where hydrolytic attack further reduces the molecular weight. Hydrogen bond cleavage between the constituents of the wood results in a loss of structural integrity and wood strength. This was very evident from runs performed with sticks. After only a 15 s steam (at 330°C) treatment, the wood, after it was dried, appeared the same as the original feed. However, there was no structural strength present, and the material was easily fragmented to a powder. As the reaction and breakdown continue, more water is released from the wood matrix and this returns to the separate aqueous phase as is shown in Figure 2. The physical destruction of wood by high temperature water was apparent from the decrease of the wood level within the basket with time. The material present originally at the top of the basket would always be found at a lower level, still only partially degraded.

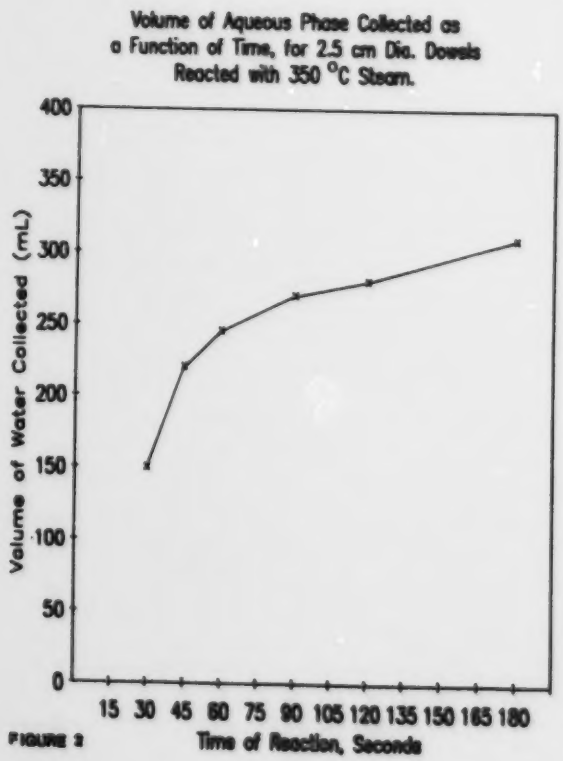

FIGURE 2

To investigate the effect of feed size on the liquefaction, experiments were carried out with chips, sticks, and dowels of various diameters. As seen in Figure 3 for 350°C runs, chips degrade to products in approximately 45 s, whereas sticks require 90-120 s for complete conversion. One hundred and eighty seconds are needed for 2.5 cm dowels. It is interesting to note that even after only 15 s of reaction time, 94% of the chips or 76% of the sticks or 57% of the 2.5 cm dowels are already lost to acetone-soluble material, aqueous phase and gas (i.e.,products). It is also found that the total conversion for 3.1 cm dowels occurs faster than for 2.5 cm dowels. A detailed explanation of this phenomenon in term of reactor size, geometry and heat transfer is given elsewhere (3).

Size study, Based on Total Conversion of Material to Products as a Function of Time for Various Sized Feeds Reacted With 350 °C Steam.

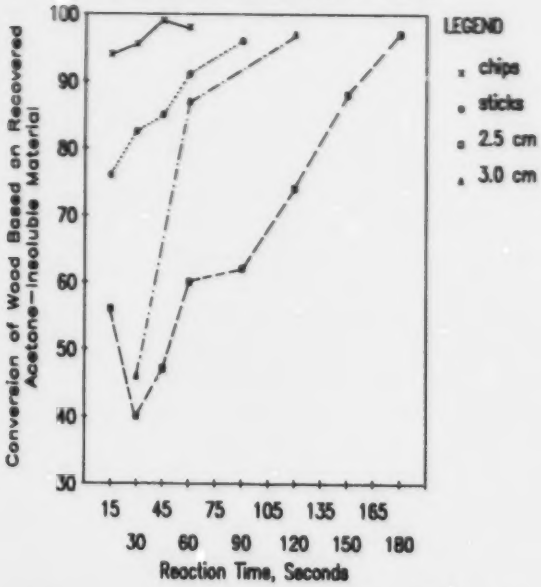

FIGURE 3

Dowel Diameter in cm.

There appears at first to be no relationship between feed size and conversion. However, each feedstock possesses a unique surface area/volume ratio, and we rationalised that this parameter should relate to the initial rate of wood conversion per unit mass or volume of the wood. Therefore, experiments were carried out with dowels, in which the grain of the wood was oriented in the usual way, that is parallel to the length. For 30 s runs, three dowel sizes (1.3, 1.75, and 2.5 cm diameter) were used. Conversion was plotted against surface area/volume ratio of the dowels (Figure 4). Two definitions of conversion were used. The first took into account only that acetone-insoluble material which remained in the feed basket. The second definition took into account the total acetone-insoluble material in the products. Figure 4 shows an apparent linear relationship between conversion and the initial surface area/volume ratio even though conversion has progressed well beyond the initial stages. The divergence of the two conversion lines shows that the smaller dowels produce more aqueous phase solids resulting from their faster breakdown. The chips show an even greater tendency to

CONVERSION VS. INITIAL SURFACE AREA/VOLUME RATIO FOR DOWELS REACTED WITH 350 °C STEAM, 30 s REACTION TIME.

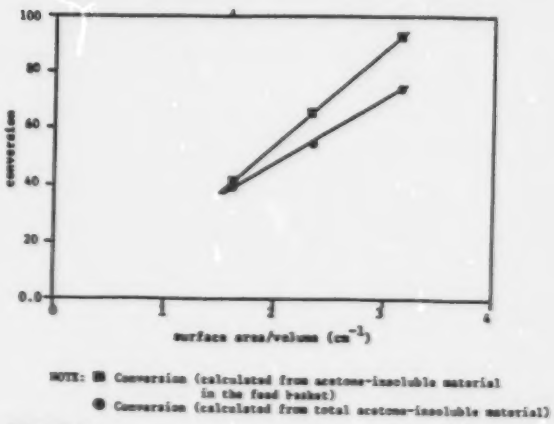

FIGURE 4

produce aqueous-phase solids. The chips therefore fragment rapidly and do not undergo a progressive inward reaction. This is because they have a larger surface area/volume ratio (5-20) than the dowels and, in addition, more end grain is exposed. This is important, since the large vessels in poplar wood will transport high pressure steam quite rapidly.

HYDRODEOXYGENATION OF WOOD OIL MODEL COMPOUNDS

The wood oils obtained from steam liquefaction contain a significant amount of oxygen (over 20% in our case), mostly in the form of phenolic and methoxy groups, and this lowers the heating values and renders the oil acidic. In order to make full use of the oil, it must be upgraded by molecular weight reduction. It might also be necessary to change the chemical composition of the oil by catalytic hydrodeoxygenation (HDO) and hydrogenation. The products could be aromatic hydrocarbons or cycloalkanes. For convenience, three model compounds (phenol, anisole, and guaiacol) were studied since they contain the two most common functionalities (aromatic OH and OCH_3) found in the oil.

All experiments, including presulfiding of catalysts, were performed in a standard 1 L stirred reactor (2). Results obtained from the use of wood oil model compounds and unsulfided and sulfided MoO_3 (15%)/CoO (4%)/Al_2O_3 catalysts are reported here.

Phenol

Phenol is of interest as an HDO model compound since a significant fraction of the oxygen in wood oil is present as phenolic hydroxyl groups. HDO of phenol for 1 hour at 450°C and 2.8 MPa initial hydrogen pressure with the MoO_3/CoO catalyst (13% of substrate weight) gave 91% phenol conversion and a product containing 67% benzene, 6% cyclohexane, and 7% methylcyclopentane. At 350°C, the sulfided form gave 65% benzene and 12% cyclohexane with 84% phenol conversion. The aromatic-cycloparaffin ratio, accompanied by good phenol conversion, was superior to the best results previously attained using unsulfided MoO_3/NiO catalyst at 450°C (4). An even higher benzene yield of 74%, with 96% phenol conversion was obtained at 375°C using the sulfided form, although the cyclohexane

yield rose to 16%. Increasing the temperature past 375°C resulted in lower benzene yields and correspondingly higher cyclohexane and methylcyclopentane yields.

Anisole

A significant fraction of the oxygen in wood oil is present in methoxyl groups, making anisole an appropriate model compound for HDO studies. The HDO of anisole was studied at different temperatures under 2.8 MPa initial hydrogen pressure using unsulfided and sulfided MoO_3/CoO catalyst (other conditions as for phenol). With the unsulfided form at 350°C, little HDO occurred, 74% phenolics (phenol and methylated phenols) and 14% anisole accounting for most of the product. At 450°C, however, extensive HDO occurred, with only 7% phenolics and 9% anisole remaining. Aromatics accounted for 62% of the product. When the sulfided catalyst was used at 350°C, only 23% phenolics and 2% anisole remained, with 56% aromatics and 11% cycloparaffins constituting the deoxygenated product. Benzene was the major aromatic product, compared to when unsulfided catalyst was used at 450°C, in which case methylbenzenes predominated.

Guaiacol

Guaiacol (1-methoxy phenol) is more representative than phenol or anisole of the compounds present in wood oil since it contains both an hydroxyl and a methoxy group. The HDO of guaiacol was studied at different temperatures under 2.8 MPa initial hydrogen pressure using unsulfided and sulfided MoO_3/CoO catalyst. With the unsulfided form at 350°C, diphenolics (catechol and dimethoxybenzene) were present in addition to phenolics, while no HDO occurred. At 400°C a maximum phenolics yield of 84% was reached. Data from the experiments in which the sulfided catalyst was used (temperature range 250-450°C) are plotted in Figure 5. The sulfided catalyst was once again found to be much more active towards HDO. At 375°C, only 15% phenolics remained, with 59% aromatics and 21% cycloparaffins comprising the deoxygenated product.

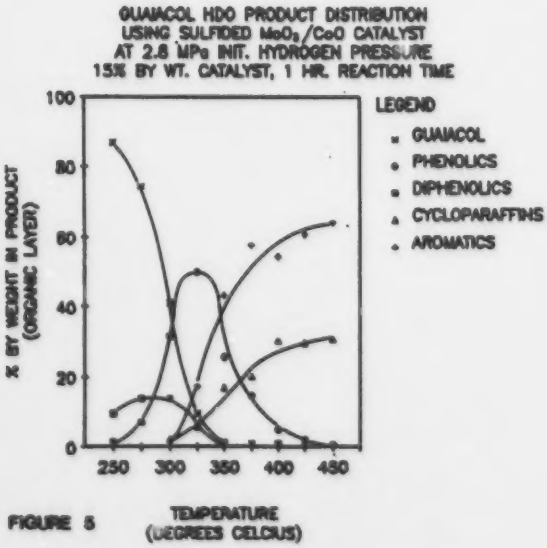

FIGURE 5

CONCLUSION

This study has shown that poplar chips, sticks and 2.5 cm dowels can be converted by 350°C steam to oil, water and gaseous products in 45 s, 90 s and 180 s respectively. Over 90% of chips, 70% of sticks, and 50% of dowels were converted to products in 15 s reaction time and using steam at 350°C. For feeds less than 2.5 cm diameter in size and using steam at 350°C, a linear relationship between conversion and initial surface area/volume ratio was found. In the wood conversion process when steam is injected into the reactor, the wood quickly absorbs much of the water available. As the reaction and breakdown occur, water is released from the wood matrix and returns to the separate aqueous phase.

It has been shown that the hydrodeoxygenation product distribution from phenol, anisole, and guaiacol can be controlled by varying reaction conditions and choosing the appropriate HDO catalyst. In particular, conventional HDO catalysts such as $MoO_3/NiO/Al_2O_3$ and $MoO_3/CoO/Al_2O_3$ can be used either in the oxidised or sulfided form to form products rich in aromatics, cycloparaffins, or phenols. These results are encouraging since they show that cracked wood oil constituents such as phenol, anisole, and guaiacol can be catalytically treated to yield selected products. Research on the HDO of wood oil is underway.

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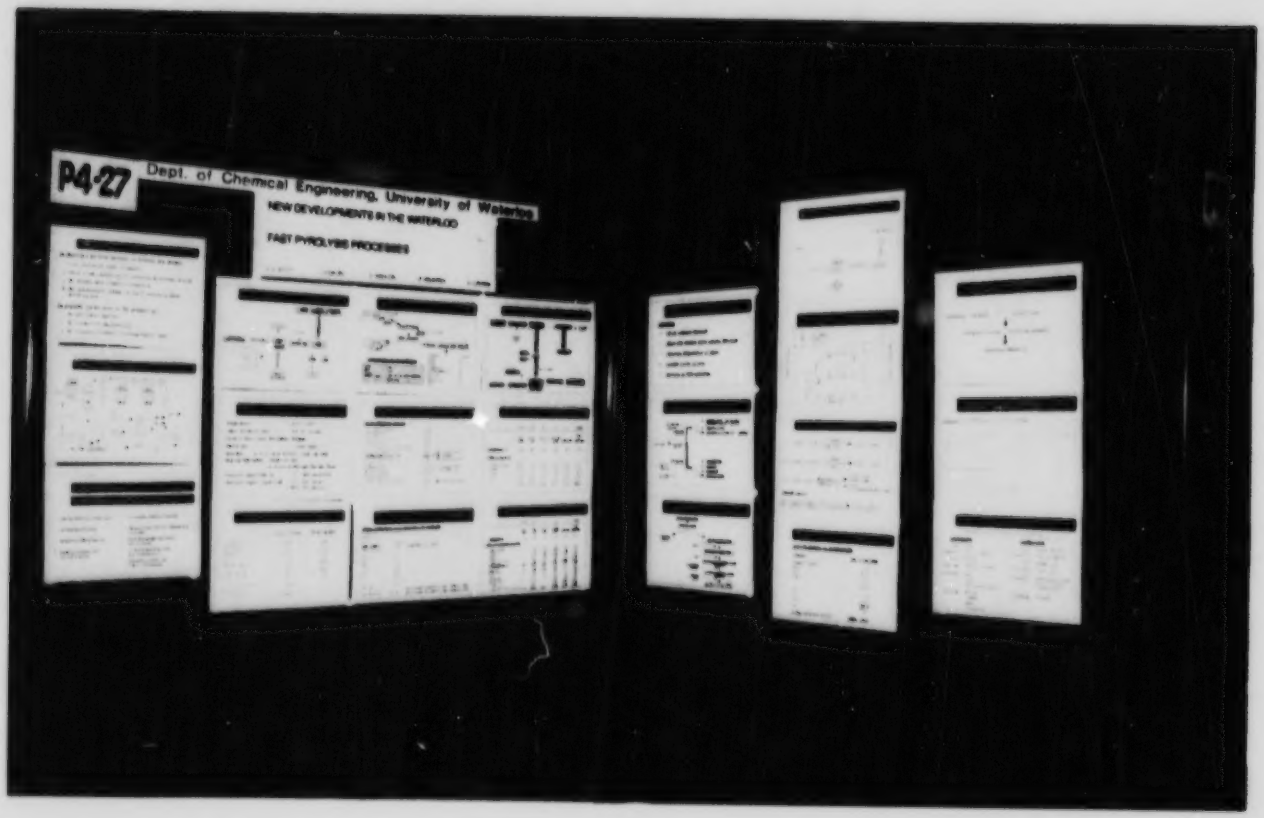
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Dept. of Chemical Engineering, University of Waterloo
NEW DEVELOPMENTS IN THE WATERLOO
FAST PYROLYSIS PROCESSES

NEW DEVELOPMENTS IN THE WATERLOO FAST PYROLYSIS PROCESS

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Over the past ten years, the Waterloo Fast Pyrolysis Process has been developed to the point at which a semi-commercial demonstration plant becomes feasible. This paper will review the various aspects of the Waterloo Fast Pyrolysis Process under the following headings, with particular emphasis on some of the more novel technology arising from this research.

a) Basic fast pyrolysis process for biomass -- results from new feedstocks, effect of particle size, properties of chars
b) Pretreatment of wood for the production of sugars from cellulose by pyrolysis; fermentation of pyrolytic sugar solutions
c) Recovery of chemicals from pyrolytic liquids
d) Hydrogasification of wood
e) Thermocatalytic conversion of wood
f) Upgrading of crude pyrolysis oils and pyrolytic lignins by hydrodeoxygenation in the Waterloo reactor
g) Demonstration plant status
h) Future work.

Les perfectionnements apportés au procédé de pyrolyse rapide de Waterloo au cours des dix dernières années ont rendu possible l'établissement d'une usine de démonstration semi-commerciale. Dans cette communication, nous passerons en revue les divers aspects du procédé de pyrolyse rapide de Waterloo, regroupés sous les titres suivants, en insistant particulièrement sur certaines des techniques les plus récentes mises au point au cours de ces recherches.

a) Procédé de pyrolyse rapide de base, applicable à la biomasse -- résultats obtenus avec de nouvelles matières de départ, effet de la granulométrie, propriétés des charbons
b) Prétraitement du bois en vue de la production de sucres à partir de la cellulose, par pyrolyse; fermentation des solutions de sucres pyrolytiques
c) Récupération des produits chimiques contenus dans les liquides pyrolytiques
d) Hydrogazéification du bois
e) Conversion thermocatalytique du bois
f) Amélioration des lignines pyrolytiques et des huiles pyrolytiques brutes par hydrodésoxygénation dans le réacteur de Waterloo
g) Démonstration de l usine
h) Travaux futurs.

INTRODUCTION

The Waterloo Fast Pyrolysis Process has been under development since 1980, with a principle objective of designing a low cost efficient process to maximize liquid yields from the fast pyrolysis of biomass. The objectives of the research are listed below.

To develop and demonstrate --

1. A process which would give maximum yields of liquids
2. A process which would have a low capital cost, in order to minimize economies of scale
3. A process which would be flexible with respect to feedstock
4. A process which would be operationally simple to allow more successful use in remote locations or in third world locales.

To evaluate market uses for products as --

5. An alternative source of fuel oil
6. A source of oxychemicals
7. A source of olefins or transportation fuels

and finally

8. To gain a better understanding of the mechanisms of rapid thermal decomposition of biomass.

Essentially all of these objectives have been achieved to a large degree. The 3 kg/h small pilot plant has been optimized and preliminary economic evaluations of a full scale process carried out. In addition, the IEA task force on biomass liquefaction has recommended the atmospheric pressure flash pyrolysis method (of which the WFPP is the most technically advanced) as potentially the most economical technology for biomass liquefaction (1).

It is now considered that the technology is ready for the demonstration plant scale and two such semi-commercial plants have been proposed, one based on wood waste as a feed, and the other based on peat feedstock.

DEVELOPMENTS

The developments which have been completed, and those which are currently the subject of research in our laboratories, are listed below, with literature references where appropriate. It will be apparent that the WFPP is, at the present time, really a group of processes using very similar pyrolysis equipment and operating conditions, but yielding a different spectrum of products for each of the process variations. These processes are shown schematically in Figure 1.

1. Basic liquefaction process for biomass -- wood, straw, bagasse, peat, bark (2)(3)(4). Unpublished results for wheat chaff, sunflower seed hulls, flax shives, hog fuel. Characterization of an alternative fuel oil.

2. The production of oxychemicals from crude pyrolysis oil -- acetic acid, formic acid, calcium acetates and formates, hydroxyacetaldehyde, acetol, glycolic acid, levoglucosan, ethylene glycol, glyoxyllic acid have all been recovered or produced (unpublished results).

3. Lignin by-product recovery and applications. Pyrolytic lignin is a low molecular weight, highly phenolic lignin. Applications in adhesives, and other phenol substitution uses are now being investigated (13).

4. The crude pyrolytic oils, as well as the separated lignin component of the oil, can be converted by hydrodeoxygenation to hydrocarbon liquids with a low oxygen content, and with a high fraction of gasoline and diesel range liquids (6)(7).

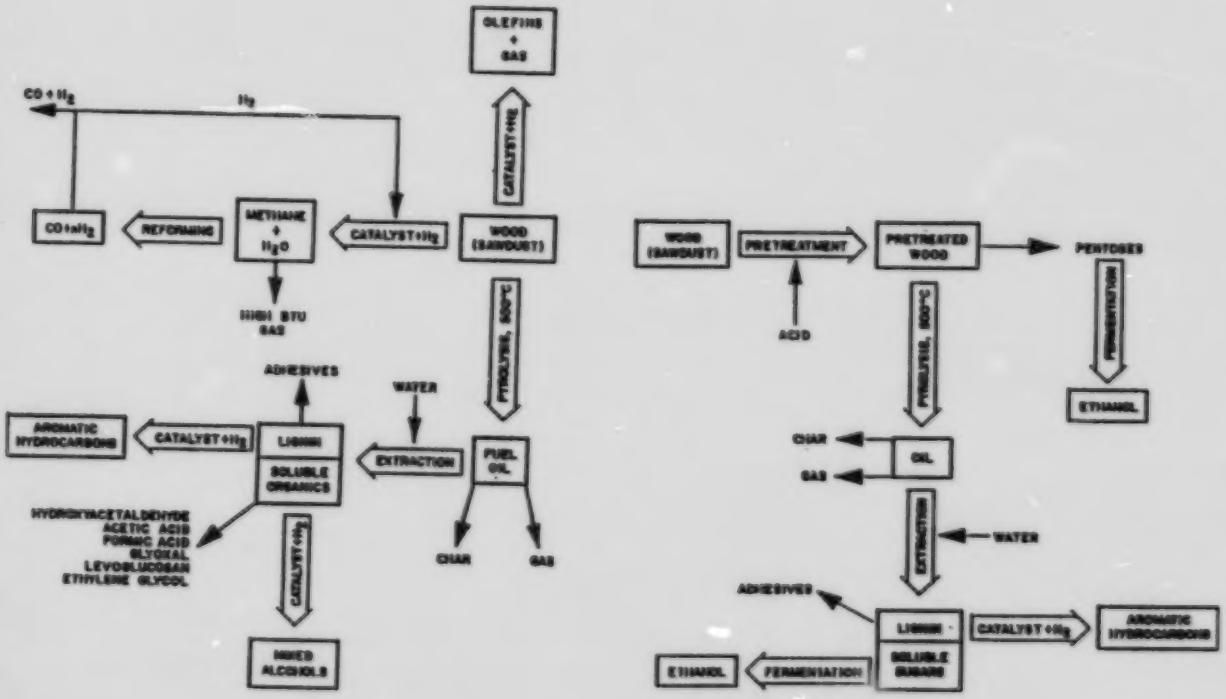

Figure 1 THE WATERLOO FAST PYROLYSIS PROCESSES

5. By suitable pretreatment of wood, the mechanism of thermal decomposition of cellulose can be changed to give high conversions to anhydro sugars and other sugars which can be readily hydrolyzed to glucose. Alternatively, the high sugar content pyrolytic syrups can be used as a source of levoglucosan. Reaction conditions are essentially the same as for other WFPP processes (8)(9)(10).

6. The high sugar content syrups obtained by WFPP pyrolysis of pretreated wood can be easily hydrolyzed and purified and then will ferment very rapidly and quantitatively to ethanol. Hydrolyzed, but not purified syrups can be fermented at normal rates with a high yield of ethanol. These syrups contain very little lignin or pentose sugars (9)(10).

7. By substituting an appropriate catalyst for sand in the WFPP fluidized bed, and using a hydrogen-rich atmosphere, wood can be converted to methane with a 75% yield based on carbon converted, giving a gas containing over 95% methane. A newly developed catalyst can improve methane yield (C-conversion) to over 90% (11)(16).

8. A number of processes are under development which are described as "Thermocatalytic WFPP" reactions. For example, wood can be directly converted at atmospheric pressure to C_2 - C_7 olefins and aromatics, with about a 35% carbon conversion. The C_4+ fraction can be as high as 30% C-conversion yield. These reactions are far from optimized, and research is in its early stages (to be presented in 1989)(11).

9. A better understanding of some aspects of the fast thermal decomposition of biomass has been gained in the course of the above developments (8)(12)(13)(14)(15).

10. Two demonstration plants are currently proposed and are in the preliminary design stage. These will both have a throughput of 200 kg/h of dry feed. One is intended for a peat feedstock and the second for a forest waste feedstock. It is hoped that these plants may start-up in early 1990.

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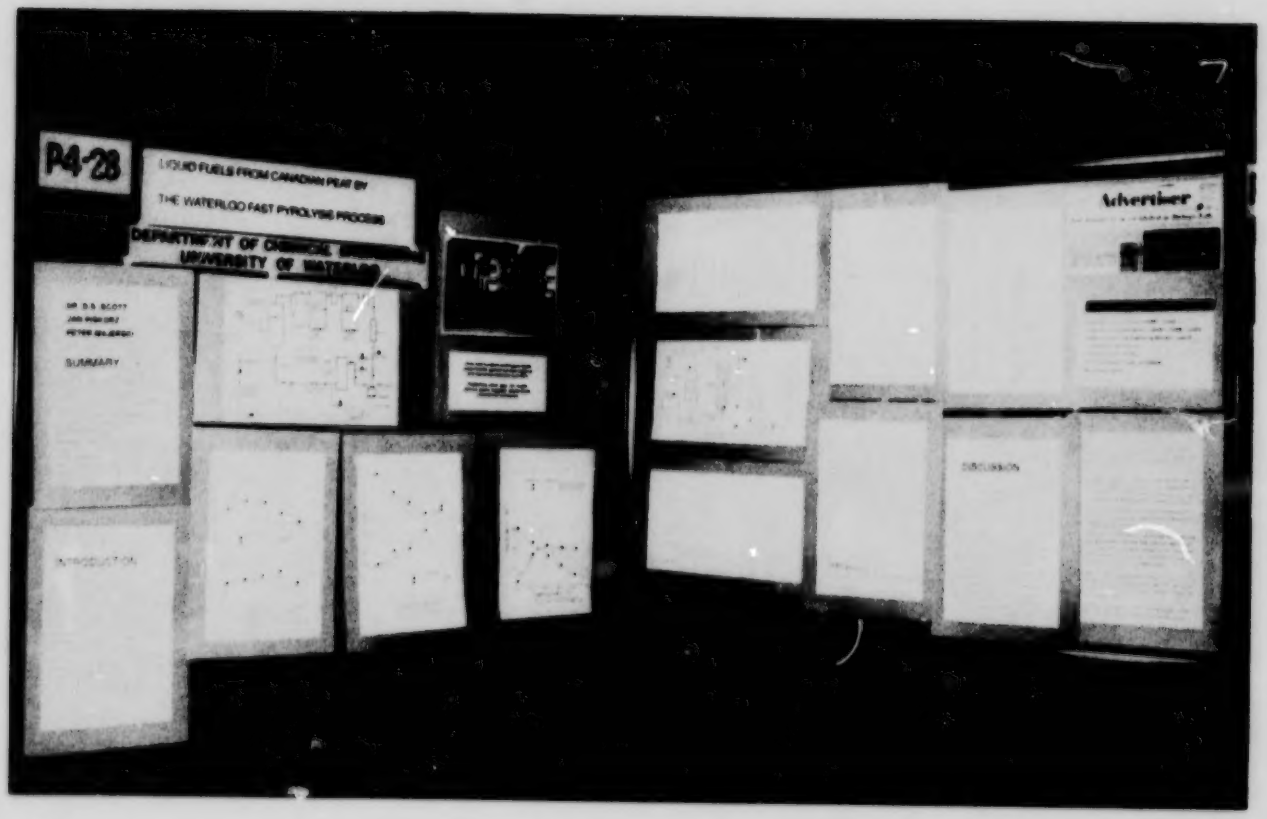
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LIQUID FUELS FROM CANADIAN PEAT BY
THE WATERLOO FAST PYROLYSIS PROCESS
UNIVERSITY OF WATERLOO
SUMMARY
DISCUSSION

LIQUID FUELS FROM CANADIAN PEAT BY THE WATERLOO FAST PYROLYSIS PROCESS

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Two Canadian peats from Quebec were pyrolyzed in the WFPP to determine maximum liquid yields possible. A young sphagnum peat (Sogovex) gave maximum yields of organic liquids (moisture free basis) of 45% to 47% in an optimum range of 450° to 550°C and one atmosphere pressure. Char yields varied from 35% to 26% and gas yields from 12% to 17% over the range. The character of the liquid product changed significantly over the optimum temperature range, with the ratio of water soluble to water insoluble components decreasing from 2.3 to 0.6, with an accompanying decrease in oxygen content.
Pyrolytic oil yields from an old black peat (Premier) gave similar results, although with somewhat lower yields of organic liquids (about 40% maximum at 500°C to 550°C). Char yield was somewhat higher at 33% at optimum conditions, but gas yields were nearly identical for the two peats.
Upgrading tests of the peat oil done in collaboration with Battelle PNWL obtained a yield of about 33% of the liquid feed as a gasoline-like liquid under hydrodeoxygenation conditions.

On a soumis deux tourbes canadiennes du Québec au PPRW (procédé de pyrolyse rapide de Waterloo) pour déterminer quels étaient les rendements maximaux de liquide pouvant être obtenus. C'est avec une jeune tourbe de sphaigne (Sogovex) que nous avons obtenu les rendements maximaux de liquides organiques (anhydres), soit 45 % à 47 % dans l'intervalle optimal de température variant de 450°C à 550°C, à une pression d'une atmosphère. A l'intérieur de cet intervalle, les rendements de charbon variaient de 35 % à 26 %, et les rendements de gaz, de 12 % à 17 %. La composition du produit liquide variait beaucoup à l'intérieur de l'intervalle optimal de température, le rapport des constituants solubles dans l'eau aux constituants insolubles dans l'eau diminuant de 2,3 à 0,6; cette diminution s'accompagnait d'une baisse de la teneur en oxygène.
Les rendements d'huiles pyrolytiques obtenues à partir d'une vieille tourbe noire (Premier) étaient analogues, quoique les rendements de liquides organiques aient été quelque peu inférieurs (maximum d'environ 40 % entre 500°C et 550°C). Dans les conditions optimales, le rendement de charbon était légèrement plus élevé, mais les rendements de gaz étaient presque identiques avec les deux tourbes.
Des essais d'amélioration de l'huile de tourbe, effectués en collaboration avec le Battelle PNWL ont permis de transformer, avec un rendement d'environ 33 %, le liquide de départ en un liquide ressemblant à de l'essence dans des conditions d'hydrodésoxygénation.

INTRODUCTION

Twelve percent of the land area of Canada can be classed as peatlands. Therefore, peat represents a very large fuel resource for Canada's future energy needs. However, at the present time, peat in Canada is produced almost exclusively for horticultural or other agricultural uses. A substantial fraction of this production of about 0.75 X 10^6 tonnes per year is exported.

Most of the available up-to-date information on Canadian peat resources and their potential for future use is available as a result of a National Energy Program established in 1982 and managed by the National Research Council until 1985 when the program was terminated. However, during this period a considerable number of studies were completed which covered resource inventory, classification, mining methods, experimental production technology, de-watering studies and various environmental studies, and which represents the best current information on Canadian peatlands and on the technology of peat production and utilization.

However, it is interesting to note that few pyrolysis studies of a Canadian peat have previously been reported. In our laboratory, we have carried out bench scale pyrolysis tests on a low grade Jamaican peat (Scott et al., 1985a), and an extensive series of bench scale tests on a Finnish fuel grade peat (Scott et al., 1988). In the latter work, the Waterloo Fast Pyrolysis Process was used, and the primary objective was the determination of optimum pyrolysis conditions for a maximum yield of organic liquids.

The present study was carried out to evaluate the fast pyrolysis of typical Canadian peats. The larger pilot plant facility (3 kg/hr) was used in order to recover sufficient quantities of liquid for characterization.

Peat is a general term which covers a very wide range of biomass materials in various stages of decomposition, occurring in a variety of environments. The characteristics of peat can vary from a near-lignite, semi-colloidal black highly humified material, to moderately or slightly decomposed grasses and mosses (brown or yellow peat). The peats currently produced in Canada are high moor younger peats, used mainly in horticultural work. Very little of the more decomposed fuel grade peat is produced. Excellent reference works and reviews on peat are available and particularly for peat conversion processes, the review by Roy et al. (1983) is recommended.

EXPERIMENTAL

Apparatus

The tests carried out in this work were all done in a small scale fluidized bed pilot plant unit, with a feed rate of up to 3 kg/hr. This apparatus and its method of operation has been described in detail by Scott and Piskorz (1984) and Scott and Piskorz (1985).

Briefly, the peat was metered by a twin screw feeder and then fed to an atmospheric pressure fluidized bed of sand in an entrained gas flow. The necessary heat for pyrolysis was supplied by preheating metered fluidizing gas. About 15% of the total inlet gas flow was used to entrain the feed. The apparent gas residence time was from 0.35 to 0.7 seconds, defined as the net reactor volume divided by the total inlet gas flow rate at reactor conditions. The gas flow rate, and sand and feed particle sizes, were selected so that the sand or the peat feed was not eluted from the bed, but the low density char formed after pyrolysis was conveyed out of the reactor into the cyclone. In effect, the residence time of the solid feed was several seconds, that is, the time required to produce a low density char.

The condensable vapours formed were collected in two vertical tube surface condensers in series, the first kept at 50°C to 80°C and the second at 0°C to 10°C. Because of the formation of tar fogs on cooling, filters were also necessary before the recycle compressor. The fluidizing gas and the feed entrainment gas were recycled product gas.

Materials Used

The peat samples were supplied by Premier Peat Moss Ltd., Rivière-du-Loup, Québec. Two samples, both sphagnum type mosses, were selected for pyrolysis, one a young horticultural peat from the top of a deposit, and the other an older black peat from the bottom of the deposit. Details of each of these samples are given in Table 1.

Table 1

Characteristics of Peat

				Analysis, % maf			
Name	Type	Moisture,%	Ash,%	C	H	N	Cellulose
Premier	Highly degraded, black	54.5	2.3	52.1	5.56	1.38	23.3
Sogevex	Young peat, blond	41.2	3.7	51.4	5.61	1.35	23.2

The Quebec Sogevex peat is a long fibred young peat suitable for some horticultural uses, and has an elemental composition not too different from wood or grasses, except for the much lower cellulose content and the higher nitrogen content, both reflecting the formation of humic acids. The Premier peat was a black, short fibre, semicolloidal material capable of very high water retention. It represents a much more degraded peat, although it is interesting to note that the cellulose content is nearly the same in the two samples, as is the elemental analysis.

Procedures

General procedures for analysis of products from a pyrolysis run have been given in previous publications (Scott and Piskorz, 1984, 1985). Gas compositions were determined from periodic sampling and chromatographic analysis of the gas product during the run, as well as from on-line CO/CO_2 infrared analysis. Char yields were obtained from the product collected from the char pot. Liquid products were collected from the two condensers, from the in-line filter, and from solvent washing of the condensers and connecting lines. Water content of each of these fractions was determined, and all liquids were then combined to give the final liquid product.

In the various pyrolysis tests carried out, the operating conditions were varied for temperature from 457°C to 692°C, for feed rate from 0.86 to 3.30 kg/h, for residence time from 0.35 to 0.55 seconds, and for feed moisture from 6.5% to 38.9%.

Liquid products were analyzed by HPLC using an Aminex HPX 87H column, isocratic, 0.07 NH_3PO_4 as eluent at a flow rate of 2.5 ml/min and a temperature of 65°C. Detection was by refractive index.

Additional details may be found in our earlier publication (Scott et al., 1988).

RESULTS

The results of pyrolysis tests carried out on the young Sogevex peat are shown in Figures 1, 2 and 3. Interestingly, temperature does not affect the yield of organics to any degree in the temperature range of 460°C to 555°C, with 44% to 49% yield mf being obtained. The yield of organics is a little higher in the 500°C to 550°C range. However, the character of the organics produced is affected significantly by temperatures in this range. Above 550°C the tar yield decreases rapidly with a corresponding increase in gas yield. It is also interesting that from 460°C to 500°C, char yield is decreased and gas yield increased, possibly indicating some incomplete decomposition of peat at the lowest temperatures. CO and CO_2 are the major gaseous products at all temperatures, but above 600°C the yield of hydrocarbon gases increases and at 692°C the yield of hydrocarbon gases reaches 7.0% of the mf feed.

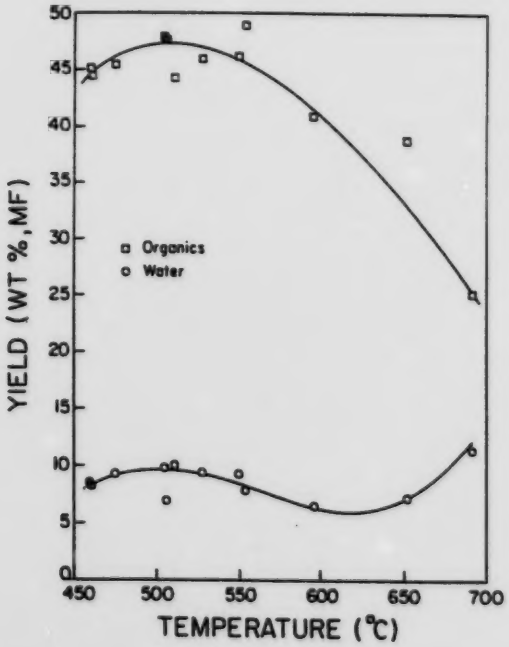

Figure 1 Pyrolysis of Sogevex Peat - Effect of Temperature on Yields of Organic Liquids and Product Water

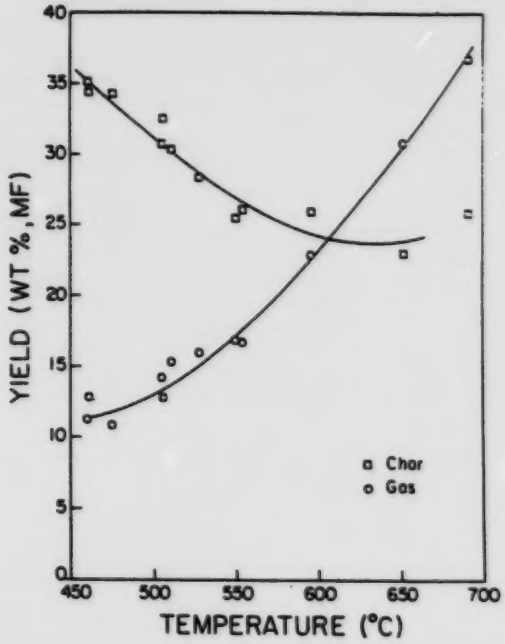

Figure 2 Pyrolysis of Sogevex Peat - Effect of Temperature on Yields of Gas and Char

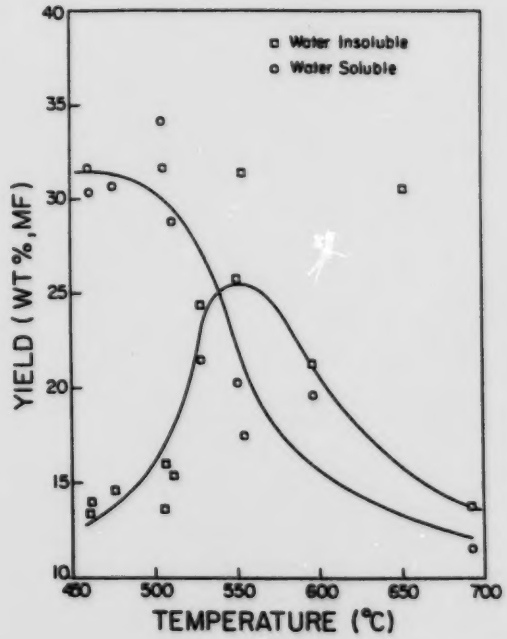

Figure 3 Pyrolysis of Sogevex Peat - Yields of Water Solubles and Water Insolubles in Liquid with Temperature Change

Figures 1 and 2 show the product yields on a moisture free basis. Maximum yield of organic liquids was obtained in the range of 475°C to 550°C, and Figure 2 shows a rather broad, flat optimum region. Char yield shown in Figure 2 decreases with temperature up to 600°C and then becomes constant. Gas yield increases steadily with temperature, suggesting that above 600°C tar yield is lost by cracking to gaseous components, and not by degradation to char.

The yields of two of the principal water soluble individual components formed from the cellulose fraction of the peat, levoglucosan and cellobiosan, are shown in Figure 3. In comparison with results from a 100% cellulose (Avicel), these yields do not display a maximum value around the optimal temperatures for liquid yield, but show a steady decrease with temperature, consistent with the decrease in the yield of water soluble material in the tar.

At the temperature of maximum liquid yield, elemental analysis showed a typical char was about 66.4% C and 2.3% H. A corresponding typical tar was about 55.8% C and 6.8% H.

Analysis by GC-MS was carried out on the whole tar from Run 102 (550°C). The total ion count chromatographs are shown in Figure 4, and the peaks tentatively identified are listed in Table 2.

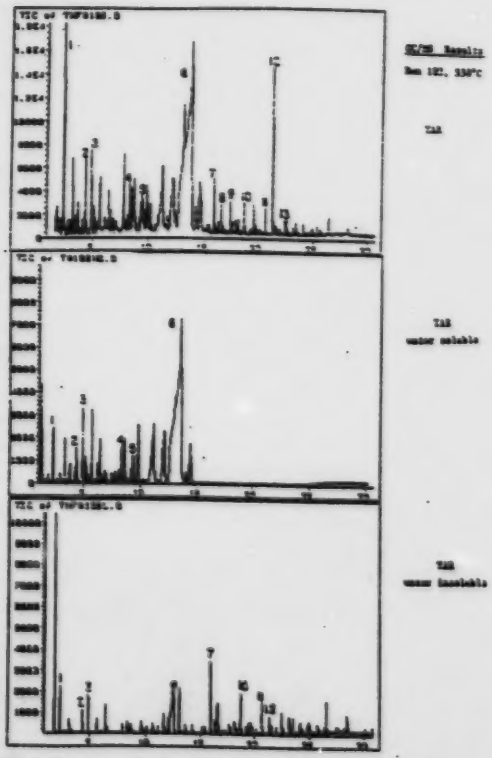

Figure 4 GC-MS Chromatogram of Peat Tar

Table 2

Gas Chromatography
Mass Spectrometry of Tar from Run 102

Identification of Major Peaks (tentative):

1. Furfural
2. Methylfurfural
3. Phenol
4. 1-2 Benzenediol
5. Xanthosine
6. Levoglucosan
7. 1-Hexanol, 4,8-dimethyl
8. 1-Eicosene
9. 4-Morpholinebutanoic acid, "alpha"
10. 1-Hexadecene
11. 11-Tricosene
12. 1,3-Benzenedicarboxylic acid, 3-butoxyether
13. 1-Hexacosene

Minor Peaks Detected	R.T.(min)
2 (3 H) Furanone, dihydro	3.1
p-Cresol	6.2
2-cyclopentene 1-one, 2,3,4 trimethyl	6.6
Phenol, 4 ethyl	7.9
Benzene, 1,4-dimethoxy	8.3
5-Hydroxymethylfurfural	8.5
Benzofuran-2,3 dihydro	8.7
1,3 Benzenediol, 3-methyl	9.0
Ethanone-1-(2-hydroxy, 5-methylphenyl)	10.1
Benzaldehyde, 4-hydroxy, 3-methoxy	11.1
Phenol-2 methoxy-5-(1-propenyl)	12.0
Phenol 2,6-bis (1,1-dimethylethyl)-4 methyl	13.1
[1,1'-Biphenyl]-3 ethoxy	15.2
1-Heptanol 6-methyl	15.5
Dodecanol 3,7,11-trimethyl	15.9
9-Tricosene	18.8
1-Docosanol	22.4
Hexadecanal	23.5
2-Heptadecanone	25.0
Undecan 5-cyclohexyl	25.7
3-Pentadecanone	26.6

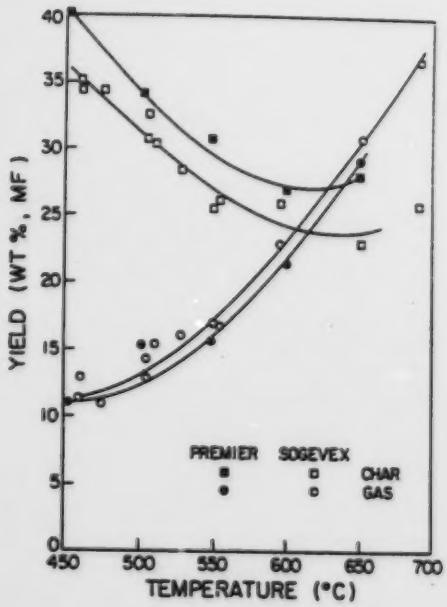

Figure 5 Comparison of Yields of Char and Gas for Premier (black) Peat and Sogevex (brown) Peat

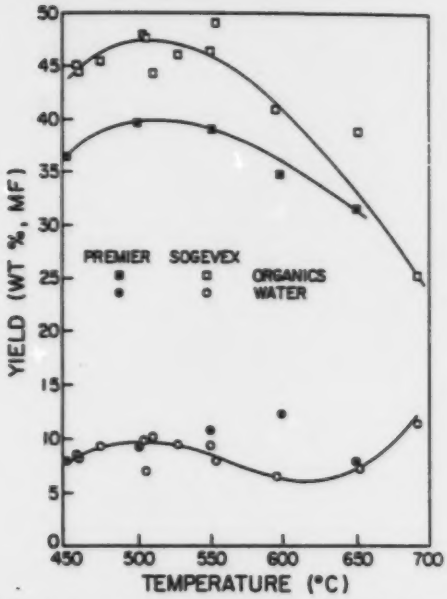

Figure 6 Comparison of Yields of Organic Liquid and Water for Premier (black) Peat and Sogevex (brown) Peat

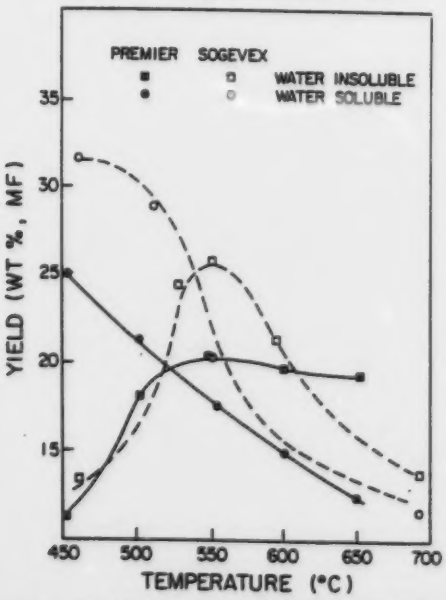

Figure 7 Yields of Water Soluble and Water Insoluble Liquid Fractions from Premier and Sogevex Peats

The results for pyrolysis tests using the low-grade Premier peat are plotted together with the results for the Sogevex peat in Figures 5, 6 and 7. Gas yields were nearly identical for the two peats, while char yield was higher by 3% to 5% for the black peat, and organic liquid yields lower by 7% to 8% at the optimal temperature of 525°C. In the optimal range, product water yield was about the same for both peats, around 10%. Considering the differences in physical nature of the two peats, the pyrolysis results are surprisingly similar. It can be inferred that most intermediate peats would give very similar results.

One of the most interesting results of this study was a rapid change in the fraction of tar which is water soluble over the region of maximum liquid yield. For Sogevex peat at 475°C, with a 47% tar yield, about 68% of this tar is water soluble. At 550°C, where the tar yield is also 47%, only about 45% of this is water soluble. At 600°C, with a tar yield of 42%, the water soluble fraction is 38% of the tar.

Yields of water soluble chemicals are plotted in Figure 7 for both the Premier and Sogevex peats. The remarkable change in the ratio of water soluble to water insoluble products observed for Sogevex peat also occurs with Premier peat, except that for the latter the ratio continues to decrease steadily as temperature increases. The reduction in liquid yields at high temperatures (600°C to 650°C) for the Premier peat, occurs almost entirely at the expense of water soluble components.

A sample of the whole pyrolytic oil prepared from the young Sogevex peat was also supplied to Battelle, Pacific Northwest Laboratories, and a hydrotreating test was carried out to attempt an upgrading of the oil to a hydrocarbon fuel. The results of this test have been reported elsewhere in full (Elliott et al., 1988).

In this catalytic hydrotreating step the crude peat pyrolysis tar was pumped through a nonisothermal reactor with hydrogen to produce hydrocarbons. During this treatment the catalytic hydrotreater at Pacific Northwest Laboratory was operated in an upflow mode through the catalyst bed of sulfided cobalt-molybdenum on alumina (Harshaw HT 400). The temperature of the bottom of the reactor was held below 300°C, and the top of the catalyst bed was near 400°C. By this type of operation, it was possible to control the pyrolytic decomposition of the peat tar and minimize coke formation in the catalyst bed. These results have also been duplicated in our laboratory at the University of Waterloo in a series of more extensive upgrading studies using a modified version of the reactor used by Elliott et al.

SUMMARY

Yellow or brown peats, short or long fibred, can be pyrolyzed readily in a fluidized bed at atmospheric pressure by the Waterloo Fast Pyrolysis Process. Maximum yields of organic liquids from a Quebec brown peat were 48% by weight of the moisture free feed. Corresponding gas and char yields were about 13% and 30%, respectively. The yield of organic liquids was nearly constant at 45% to 48%

over the temperature range 460°C to 550°C. However, the character of the liquid changed over this temperature span with a steadily decreasing amount of water soluble product, and an increasing amount of water insoluble product.

Organic liquid yields from a low grade black fuel grade Quebec peat were somewhat lower than those from brown peat (40% mf vs. 47% mf) with corresponding increases in char yield. However, considering the difference in peat quality, yields of pyrolysis products were surprisingly similar.

Peat oil can be upgraded by high pressure catalytic deoxygenation/hydrogenation to give a gasoline range liquid with a yield of about 18% of the peat fed (mf), or about 38% of the peat oil produced.

ACKNOWLEDGEMENT

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CONVERSION OF LIGNOCELLULOSICS TO SUGARS BY THERMAL FAST PYROLYSIS

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It is well known that slow heating in vacuum of a purified cellulose will give significant yields of anhydrosugars, principally levoglucosan. However, these high conversions are not obtained in fast pyrolysis of cellulose, and fast or slow pyrolysis of wood or other lignocellulosics gives low yields of anhydrosugars.
It is possible to obtain conversions of the cellulose content of wood of up to 80% (glucose equivalent) if the biomass is given an appropriate pretreatment and then subjected to a fast pyrolysis process such as the Waterloo Fast Pyrolysis Process. In order to obtain maximum conversions of the cellulose content of wood to monomeric sugars by purely thermal decomposition at least four parameters must be controlled during the pretreatment step; the degree of polymerization, amounts and types of inorganic anions and cations, the degree and method of removal of hemicellulose, and the level of alteration of the lignin content. Results are given for experiments with several feedstocks which show some of the effects of each of these parameters on the yields of monomeric sugars.
A preliminary estimate of costs of producing fermentable sugars by this method is given. The results of some preliminary fermentation tests are also given.

On sait que le chauffage lent sous vide d'une cellulose purifiée donnera des rendements importants en sucres anhydres, principalement en lévoglucosane. Toutefois, ces taux élèves de transformation ne peuvent être obtenus par pyrolyse rapide de la cellulose et la pyrolyse, rapide ou lente, du bois ou d'autres produits lignocellulosiques donne des rendements peu élèves de sucres anhydres.
Il est possible d'obtenir des taux de transformation allant jusqu'à 80% de la teneur en cellulose du bois (équivalent de glucose) si la biomasse est soumise à un pré-traitement approprié, puis à une pyrolyse rapide comme le procédé de pyrolyse rapide de Waterloo. Pour obtenir des taux maximaux de transformation de la cellulose contenue dans le bois en sucres monomériques, par décomposition purement thermique, il faut agir sur quatre paramètres pendant le pré-traitement: le degré de polymérisation, les quantités et les types d'anions et de cations inorganiques, le degre et la methode d'elimination de l'hemicellulose et le degré de modification de la teneur en lignine. On donne les résultats d'expériences réalisées avec plusieurs matieres de base, qui montrent certains des effets de chacun de ces paramètres sur les rendements en sucres monomériques.
On fournit une évaluation préliminaire des coûts de la production de sucres fermentescibles par cette méthode. Les résultats de certains essais préliminaires de fermentation sont également indiqués.

INTRODUCTION

Over the last several years, the Waterloo Fast Pyrolysis Process (WFPP) has been developed to maximize yields of liquids by the rapid thermal decomposition of lignocellulosic biomass. The process operates at atmospheric pressure and the reaction is carried out in a fluidized bed of sand as a heat transfer medium. Optimal conditions for woody biomass are 450°C to 550°C and about 0.5 seconds gas residence time. The nature of the fluidizing gas has little influence on yields.

Liquid yields from wood at optimal conditions are 70% to 80% of the dry feed, with the organic liquid yields being 60% to 65% of the dry wood fed. A description of the process and the yields obtained with various types of biomass has been published previously by the authors [1][2]. Extensive identification and quantification of many of the individual compounds present in these pyrolytic oils has also been reported [3][4][5].

It has been known for many years, as described in the extensive literature on the subject, that slow heating of cellulose under

vacuum can lead to significant yields of anhydrosugars, principally levoglucosan. However, pyrolysis of wood, whether slow or rapid, normally gives very low yields of levoglucosan. Instead, lower molecular weight oxygenated compounds are the major products, and, as pointed out by the authors in a previous publication [6], if fast pyrolysis is employed, then hydroxyacetaldehyde will be one of the principal products. In that publication, a mechanism was also proposed to account for the formation of hydroxyacetaldehyde, in which it was assumed that levoglucosan was a precursor, and that lower molecular weight products were formed in successive sequential decomposition steps. However, more recent work has led us to believe that levoglucosan and hydroxyacetaldehyde are produced in parallel reactions, a mechanism which has also been proposed recently by Richards [7].

Shafizadeh and Stevenson [8] suggested that the yield of levoglucosan from wood could be increased by pretreatment of the wood to remove hemicelluloses prior to pyrolysis. Radlein et al. [9] in 1987 reported the results of preliminary experiments which showed that a mild acid hydrolysis of wood followed by fast pyrolysis completely changed the product spectrum, and, in particular, greatly increased the yields of levoglucosan and other sugars.

Additional experimental results are given here of investigations of the effects of various pretreatment of wood on the yields of anhydrosugars. A conceptual scheme for the production of sugars from wood by fast thermal pyrolysis together with some preliminary economic estimates are presented. The results of initial fermentation tests of the products are also reported.

EXPERIMENTAL

Samples tested included poplar woods, both untreated as well as subjected to a variety of pretreatments and a pretreated pine.

The St. Lawrence poplar [11] was prehydrolysed with 0.5% HCl at 165°C for 6 minutes in a plug-flow reactor -- a procedure which led to substantial hemicellulose removal. Wayman poplar [12] was whole wood pretreated with 2% SO_2 at 200°C for 45 seconds in a Wenger extruder. Biohol pine [13] was autoclaved with 3% SO_2 at 110°C for 2 hours. Hemicelluloses were partially removed by this treatment. Stake poplar [14] was steam-exploded wood after digestion at 322 psi for 2 minutes.

The acid-hydrolysed samples were prepared by boiling the ground wood meal in 5% H_2SO_4 for 2 or 6 hours as indicated in the tables, except in the case of the Stake wood which was treated with cold (21°C) 5% H_2SO_4 for 21 hours. Following the acid treatment the samples were washed with deionized water till acid-free. "Deionized" wood was prepared by percolating 10 cm^3 g^{-1} of cold 0.1% H_2SO_4 through a column of clean wood meal at a rate of about 2 cm^3 hr^{-1} (g wood)$^{-1}$, followed by washing with distilled de-ionized water at a similar rate until the wash was acid-free.

Analysis of acid hydrolysate and of the water extract of the pyrolysis oils was done by HPLC (Aminex HPX-87H column at 65°C, eluent 0.07N H_3PO_4, eluent flow rate 0.32 x 2.25 ml/min).

Except where otherwise noted, pyrolysis of raw or treated wood or cellulose was carried out at standardized conditions near optimal for the Waterloo Fast Pyrolysis Process for all runs, that is at 500°C, 0.46 to 0.50 seconds apparent gas residence time, nitrogen atmosphere, employing the bench scale fluidized bed unit which has been described in detail elsewhere [1].

Ash analysis was carried out by slow controlled combustion of biomass in a muffle furnace at 650°C to prevent loss of volatile inorganic salts. It was estimated that this method gave ash values accurate to 0.01 weight percent.

Cellulose content was determined by gravimetry of the residue remaining after hemicelluloses and lignin were dissolved in a mixture of acetic and nitric acids according to the procedure of Updegraff [10].

RESULTS

The "commercial" feedstocks were pyrolysed without further pretreatment with the results shown in Table 1. Results for untreated clean IEA poplar are included for comparison. Pyrolytic lignin is the water insoluble portion of the tar [5]. Only the (anhydro) sugars and hydroxyacetaldehyde from among the water-soluble components are listed. Total liquid yields (water + organics) for the pretreated materials range from ~61% (Biohol) to 81% (St. Lawrence) compared to 78% for the untreated wood. Sugar yields were in all cases relatively low. In the best case (Wayman) 35.5% of the cellulose was converted to sugars.

Some of these materials were then subjected to hydrolysis with H_2SO_4 as described in the experimental section. This procedure causes extensive hemicellulose removal resulting in an enhanced cellulose content. Ash levels are also reduced. The results of pyrolysis of the hydrolysed substrates are listed in Table 2. In all cases there is a sharp increase to ≥66% conversion of cellulose to sugars. It should be pointed out that the "char" in these cases is not solely primary but includes a fused material accumulated at the reactor outlet and having the appearance of a carbonized liquid.

An attempt was made to identify the important variables controlling sugar yields. Clean IEA poplar was hydrolysed with H_2SO_4 in the

Table 1

Pyrolysis of Raw and Pre-Treated Wood

Run No.	A-2	1-DL	18	20	30
Feedstock	IEA Poplar	St.Lawrence Poplar	Wayman Poplar	Michel Pine	Stake Poplar
Cellulose Content, % mf	49.1	65.4	43.1	54.9	47.8
Ash, % mf	0.46	0.05	1.8	1.0	0.47
Temperature, °C	497	400	500	500	500
Yields, wt % mf					
Gas	10.0	7.6	14.0	7.5	13.0
Char	7.7	10.1	11.9	23.0	12.4
Water	12.2	2.9	8.5	10.6	3.2
Organics	65.8	78.4	63.2	51.0	58.9
Total Recovery	96.5	99.8	97.6	92.1	87.3
Levoglucosan	3.0	4.5	6.7	10.3	2.9
Other Sugars	6.1	5.1	8.6	4.7	1.1
Hydroxyacetaldehyde	10.0	9.1	7.4	Trace	7.5
Pyrolytic Lignin	16.2	18.8	19.3	21.9	18.0
% Cellulose Converted to Sugars	18.5	14.7	35.5	29.1	8.5

Table 2

Pyrolysis of Some Acid-Hydrolysed Woods

Run No.	10	14	46
Feedstock	IEA Poplar	St.Lawrence Poplar	Stake Poplar
Cellulose Content, % mf	65.5	70.6	66.5
Ash, % mf	0.02	0.30	0.16
Hydrolysis Time, hours	6	2	2
Temperature, °C	480	480	490
Yields, wt % mf			
Gas	6.9	6.4	6.6
Char	8.2	10.5	6.7
Water	[illegible]	5.2	3.2
Organics	80.9	75.0	82.1
Total Recovery	98.2	97.1	98.6
Levoglucosan	30.0	30.1	25.3
Other Sugars	13.2	18.8	20.2
Hydroxyacetaldehyde	0.9	0.9	4.3
Pyrolytic Lignin	21.0	17.9	18.8
% Cellulose Converted to Sugars	66.0	69.3	68.4

manner already described and pyrolysed at different temperatures and feed rates, with varying water content and, in one case, with an additive (NH_3). The results are summarized in Table 3 which includes a detailed breakdown of the compositions of the gas and the water-soluble organics. In some cases a distinction is made between the primary char and fused materials ("coke"). In all cases primary char yields are nearly zero. Liquid yields are uniformly high and gas yields correspondingly low as would be expected from the pyrolysis of similarly treated substrates (cf. Table 2). In the case of Run S#1, following hydrolysis the lignocellulose was steeped in dilute NH_3 for one hour, washed till ammonia free and dried. Only in this case is the sugar yield significantly suppressed. Otherwise no clear trends emerge of the effects of hydrolysis time, moisture content, pyrolysis temperature, particle size or feed rate.

We have also made a preliminary investigation of the feasibility of obtaining high sugar yields from wood without preliminary hydrolysis of hemicelluloses. For this purpose "de-ionized IEA poplar was prepared in the manner already described. In some cases 0.1 wt% of $(NH_4)_2SO_4$ or H_2SO_4 was added to the de-ionized wood by dissolving in a sufficient amount of water to saturate the wood then drying at 105°C for one hour. The results of these tests are shown in Table 4. Sugar yields are good with a presumably catalytic enhancement by small amounts of $(NH_4)_2SO_4$ or H_2SO_4. Though less than those from lignocellulose (i.e. acid hydrolysed wood) they are a great deal better than those from untreated wood. To our knowledge they are the highest ever reported from whole wood.

DISCUSSION

The factors which determine the yield of levoglucosan from cellulose pyrolysis have been extensively studied. (For a review see Ref. [5]). Apart from the hydrodynamic and temperature regime, various intrinsic factors like cellulose morphology and degree of polymerisation have been cited. Definitive evidence has been hard to come by but one of the most clearly established effects is the role of certain types of cations, especially alkaline and alkaline earth, in catalysing fragmentation and charring reactions and suppressing levoglucosan yields in even trace amounts. Most of the published studies of cellulose pyrolysis relate to slow, low temperature vacuum conditions. The results from de-ionized wood indicate that the deleterious effects of cations persist in the case of fast high temperature pyrolysis of whole wood (cf. Runs A-2 and S#3 in Tables 1 and 4 respectively).

This cation effect appears to be one of the principal reasons why the commercial pretreated wood samples gave only poor to modest yields of sugars. It will be noticed from Table 2 that acid hydrolysis of these samples caused substantial reductions in ash content. (Most of the remaining ash is likely to be inert material like silica.) In fact the data suggest that a mild cold de-ionization of these samples is likely to cause substantial

enhancement of sugar yield. The best results in Table 1 are for the SO_2 treated materials (Waysen and poplar and Biohol pine). It is possible that this treatment causes other changes which are conducive to sugar formation. On the other hand the Stake wood gave excellent results after a cold acid wash.

Acid hydrolysis under the conditions used also causes hemicellulose removal. Our data (Table 4) confirm an earlier observation by Shafizadeh and Stevenson [8] that, provided soluble ionic substances are removed, the presence of hemicellulose in wood is not, per se, detrimental to levoglucosan production. (Cations in fact would be expected to associate with carboxylic groups in hemicellulose.) The best results with de-ionized wood are not quite as good as those with lignocellulose but no definite conclusion can be drawn as the degree of de-ionization has not been optimized.

It might be supposed that hemicellulose could play a physical role in denying free passage to the escaping sugars, but this is not necessarily true either. In the first place hemicellulose tends to decompose at a lower temperature than cellulose. Besides, the pyrolytic behaviour of substrates which give high sugar yield is markedly different from that of untreated wood. When untreated wood particles are dropped on to a hot plate at 250°C to 300°C, they char and ignite. On the other hand, de-ionized wood and acid-hydrolysed lignocellulose undergo instantaneous melting without ignition. The complete absence of primary char from lignocellulose pyrolysis is in congruence with these observations. In that case sugar yields would be determined principally by factors such as heating rate, rate of diffusion in the liquid phase and volatilization rate, with the latter being the most likely rate limiting step. The absence of any apparent particle size effect (see Table 3) is in agreement with this.

Table 3

Pyrolysis of IBA Ligno-Cellulose Under Varying Conditions

Run No.	A-1	SY-10	SY-11	S/0	S/1[a]
Temperature, °C	501	480	475	505	485
Feed Rate, g/hr	46.9	71.5	116	33.2	41.6
Hydrolysis Time, hr	6	6	2	2	2
Moisture, wt %	16.5	6.5	6.0	7.5	13.7
Particle Size, mm	-0.25	-0.5	-0.5	-0.5	-0.5
Yields, wt % af					
Gas	6.4	6.9	6.4	4.3	4.3
Char	-0	} 8.2	} 6.3	-0	-0
Coke	6.7			4.7	4.2
Organics	79.6	80.9	73.6	73.6	78.1
Water	8.9	2.2	6.3	12.0	9.6
Total Recovery	93.6	98.2	92.6	94.6	96.2
CO	2.79	2.13	2.5	1.86	1.96
CO_2	3.07	2.29	1.9	2.08	1.93
CH_4	0.38	0.6	0.4	0.33	0.33
C_2^+	0.10			0.06	0.11
Oligosaccharides	1.19	0.69	0.89		2.56
Cellobiosan	5.68	4.74	4.77	9.31	6.05
Glucose	1.89	1.34	1.96		
Fructose (?)	3.89	2.21	2.12	3.49	2.01
Glyoxal	0.11	0.28	0.28	3.66	2.32
1,6-Anhydroglucofuranose	4.50	3.90	3.89	3.49	2.40
Levoglucosan	30.42	30.0	28.7	26.94	19.80
Hydroxyacetaldehyde	0.37	0.9	0.9	3.73	3.96
Formic Acid	1.42				4.96
Formaldehyde	0.8	2.36	1.06		
Acetic Acid	0.17	2.32	1.03		0.70
Acetal	0.06	0.07	0.12		
Pyrolytic Lignin	19.0	21.0	21.8	22.9	23.9

[a] NH_3 treated. See text.

Table 4

Pyrolysis of De-ionized IBA Poplar

Run No.	S/3	S/4	S/5	S/6	S/7
Temperature, °C	530	~530	~530	493	495
Feed Rate, g/hr	8.0	22.3	18.3	23.6	27.1
Additive (wt %)[a]	0	N (0.1)	N (0.1)	N (0.1)	N (0.1)
Moisture, wt %	0	3.0	28.9	11.4	7.0
Particle Size, mm	-0.5	-0.5	-0.5	-0.5	-0.5
Yields, wt % af					
Gas	14.13	7.35	6.63	2.61	3.22
Char	} 2.5	1.66	} 3.93	0.67	0.72
Coke		2.77		4.68	5.41
Organics	60.50	66.07	75.24	75.93	66.10
Water	18.25	16.20	5.70	2.67	~17
Total Recovery	95.38	94.05	91.50	97.85	92.45
CO	4.86	3.86	2.94	trace	0.61
CO_2	0.75	2.98	3.09	2.37	2.27
CH_4	0.38	0.60	0.47	0.24	0.29
C_2^+	0.13		0.13		0.05
Oligosaccharides	-	-	-	-	-
Cellobiosan	4.92	2.46	1.35	1.92	1.68
Glucose	0.94	0.98	0.81	1.12	1.00
Fructose (?)	1.81	1.54	1.22	1.92	1.84
Glyoxal	2.86	2.96	2.34	2.65	2.26
1,6-Anhydroglucofuranose	1.13	2.76	2.24	2.87	2.72
Levoglucosan	9.33	18.73	16.53	17.11	15.52
Hydroxyacetaldehyde	3.35	3.26	2.57	1.95	1.65
Acetic Acid	0.67	1.41	1.15	1.34	1.17
Pyrolytic Lignin	17.8	~21	18.9	22.4	23.1
% Cellulose Conversion to Sugars	37.1	53.9	45.1	50.8	46.4

[a] N = $(NH_4)_2SO_4$, N = H_2SO_4

The other principal question addressed by our data concerns the precise role of acids. Apart from cation and/or hemicellulose removal, the data in Table 4 clearly show what appears to be a positive catalytic effect. Such an effect has been previously postulated by Shafizadeh [8]. $(NH_4)_2SO_4$ decomposes at 235°C to free H_2SO_4 (b.p. 338°C and volatile NH_3 gas which probably readily escapes. By this strategy the timing of the release of acid is controlled and the problems of drying samples containing H_2SO_4 are avoided. (When the substrate of Run S#7 was dried some surface charring was clearly visible -- a fact which might be contributory to the lower sugar yields.) There remains a great deal of scope for optimizing the chemical nature, the quantity and the manner of incorporating acid into wood or lignocellulose.

The fact that NH_3 treatment of the acid hydrolysed lignocellulose caused a substantial reduction in sugar yield (Run S#1 in Table 3) appears at first sight to be somewhat puzzling in the light of the results from deionized wood. In fact our working hypothesis for NH_3 addition was that during acid hydrolysis H_2SO_4 condensed with cellulosic hydroxyl groups to form sulfate esters ($R\text{-}O\text{-}SO_2OH$) which are retained in the substrate and hence become available for catalysis. Addition of NH_3 (cold) would neutralise these groups and release free acid only at elevated temperatures. It is not possible to make a definitive statement at this time but it once more suggests that the type and quantity of acid have an important bearing on its catalytic role.

One final point concerns the completeness of the characterisation of the water-soluble portion of the organic liquid. We are able to identify by HPLC an average of only 73% for the wood samples in Table 4 compared with 85% to 95% for the lignocelluloses in Table 2. GCMS showed the presence of significant quantities of two unidentified components in the wood tars which were absent from the lignocellulose, suggesting a hemicellulose origin. Preliminary work indicates they are anhydro-xylan substances but positive identification has not yet been established.

We summarize our principal conclusions as follows

(a) It is possible to obtain yields of anhydrosugars from wood and lignocellulose by fast high temperature pyrolysis.

(b) The highest yields were obtained when the feedstock was pretreated in a suitable way. Acid hydrolysis or acid washing proved to be very effective leading to over 65% conversion of cellulose to sugars in the most favourable cases.

(c) The acid appears to play at least two critical roles; to remove harmful cations and to catalyse anhydrosugar release.

(d) However, much more fundamental work remains to be done to gain a full understanding of the effects of both pretreatment and pyrolysis variables on sugar yields.

PRODUCTION AND USE OF SUGARS PREPARED BY WFPP

A conceptual flowsheet of a possible process for the production of fermentable sugars from lignocellulosic biomass is shown in Figure 1. In this process, wood is ground and then given a mild prehydrolysis with sulfuric acid. The pretreated wood after decanting is then washed in a countercurrent washer. Some of the liquid product from these steps is recycled to increase pentose concentration, while some can be used as a quench stream in the pyrolysis product collection system. The pretreatment hydrolysate contains 50% to 60% of the hemicellulose content of the wood as xylose.

After washing and drying the wood is pyrolyzed in an atmospheric pressure fluidized bed reactor operating at optimal conditions for the Waterloo Fast Pyrolysis Process (WFPP). The char and gas products are used for process heat requirements. The pyrolytic sirup is condensed and extracted with water to precipitate the lignin derived fraction which can be removed by centrifuging. The resulting crude aqueous solution of sugars and anhydrosugars is then hydrolyzed by dilute acid, or other reagent, to glucose, to give a solution with a final concentration of 100 to 300 g/litre of glucose.

A preliminary estimate of costs for this process for a relatively small plant with a capacity of 70 dry tonnes/day of poplar wood gave a capital cost of about $4.5 million (Canadian). Assuming a raw material cost as waste wood available at a single site (the reason for the smaller plant size) of $40 per dry tonne, a 50/50 debt/equity ratio with financing costs at 12% and a 30% return on investment, a selling price of 23.4¢/kg for hexose and pentose product is estimated. A credit of 10¢/kg has been assumed for the lignin product in this estimate. Excluding ROI and financial costs, a manufacturing cost of 18.6¢/kg (8.5¢/lb) for the hexose-pentose products is obtained.

Fermentation tests were carried out by an independent consultant on products produced from the pilot plant scale pyrolysis reactor (3 kg/hr feed). The anhydrosugars as produced can be fermented only slowly, if at all, by the common ethanol producing yeast strains. After hydrolysis of these anhydrosugars to glucose, however, fermentation proceeded to completion at a normal rate with common bakers yeast, that is, in about 24 hours. If the hydrolyzed sirup of hexoses was treated with activated carbon before fermentation, quantitative conversion to ethanol occurred in 1.5 hours.

WOOD PYROLYSIS PLANT FLOWSHEET

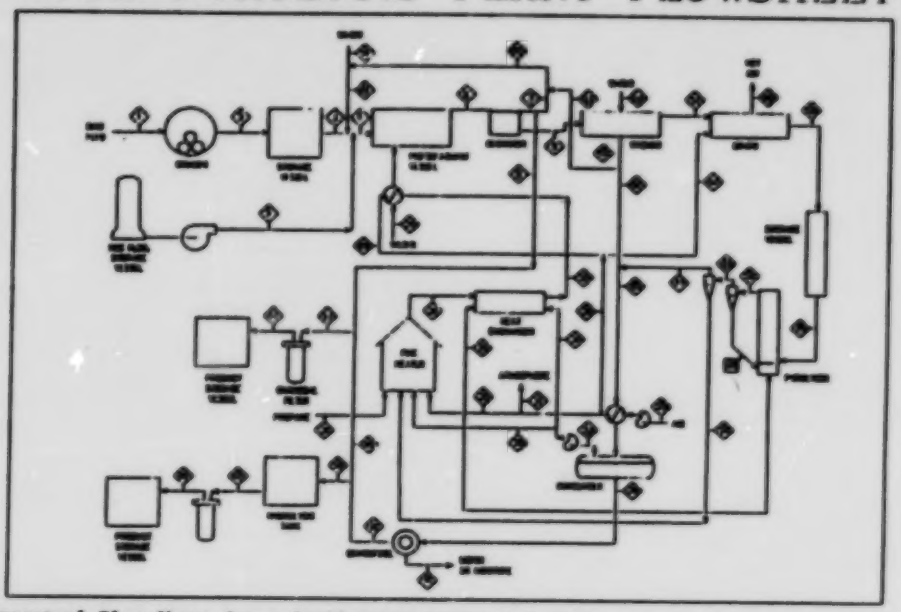

Figure 1 Conceptual Flow Sheet for a Small Scale Commercial Plant for the Production of Sugars from Wood by Fast Thermal Pyrolysis

In summary, it appears that the thermal conversion of wood or cellulose after suitable pretreatment is a viable and potentially economic approach to the production of fermentable hexoses and pentoses from cellulose and hemicellulose fractions of lignocellulosic biomass. Further optimization of the process will probably lead to cost reductions also.

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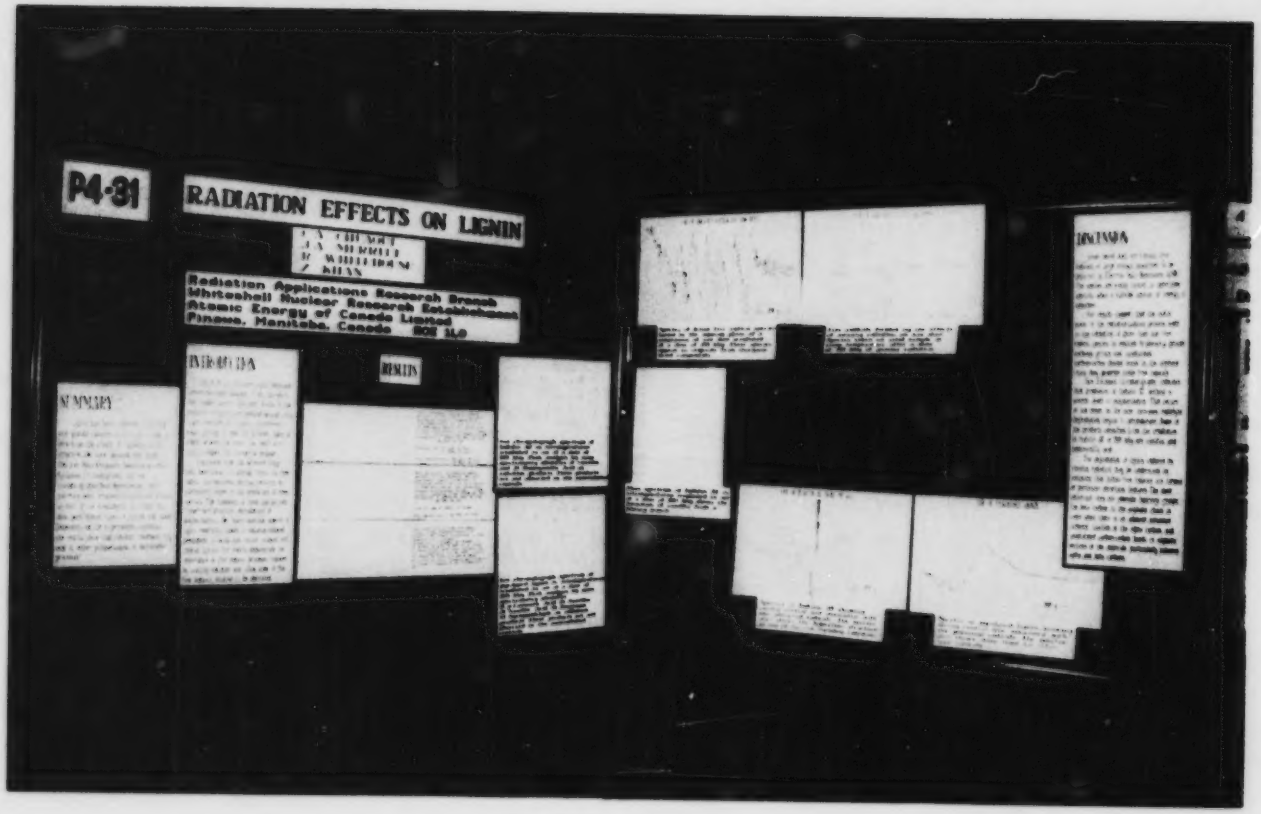
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RADIATION EFFECTS ON LIGNIN
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Pinawa, Manitoba, Canada
SUMMARY
INTRODUCTION
RESULTS
DISCUSSION

RADIATION EFFECTS ON LIGNIN

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Lignin has been subjected to electron and gamma radiation as part of a study to determine the effects of radiation on its structure. Some of the factors that influence the outcome of the treatment are the dose, the nature of the atmosphere surrounding the sample, and the physical state and nature of the irradiated lignin itself.
We have obtained data to describe some of the free-radical intermediates formed during irradiation and how the variation of some of the factors affects the magnitude and direction of the effects induced by irradiation. The data were obtained from Electron Spin Resonance Spectroscopy, Size Exclusion Chromatography and other High Performance Liquid Chromatography techniques, Gas Chromatogrphy-Mass Spectroscopy analysis, and chemical degradative methods. Solid Materials were irradiated in different solvents as part of the experiments. The substrates used were several types of isolated lignins and wood, and some compounds that are useful as lignin models. Depending on the experimental conditions, the results show that radiation treatment may lead to either polymerisation or degradation processes. The factors that determine the outcome are discussed in terms of the structure of the substrates and the chemical processes that take place.

La lignine a été exposée à des rayonnements électroniques et à des rayonnements gamma dans le cadre d'une étude visant à déterminer les effets de ces rayonnements sur sa structure. Parmi les facteurs qui influent sur le résultat du traitement, on compte la dose, la nature de l'atmosphère entourant l'échantillon ainsi que l'état physique et la nature de la lignine irradiée elle-même.
Nous avons obtenu des données pour décrire certains des intermédiarires de type radical libre formés pendant l'irradiation et comment la variation de certains des facteurs touche l'intensité et le sens des effets induits par irradiation. Les méthodes suivantes ont été utilisées pour recueillir ces données: spectrométrie de résonance paramagnétique électronique, chromatogrphie de perméation sur gel et autres techniques de chromatographie en phase liquide haute performance, analyse par chromatographie en phase gazeuse/spectrométrie de masse et méthodes de dégradation chimique.
Dans le cadre des expériences, les solides ont été irradiés dans différentes atmosphères et les suspensions l'ont été dans différents solvants. Les substrats utilisés étaient constitués de divers types de lignines et de bois isolés ainsi que de certains composés utiles en tant que modèles de la lignine. Les résultats montrent que selon les conditions expérimentales, l'irradiation peut donner lieu ou bien à une polymérisation, ou bien à une dégradation. On expose les facteurs qui déterminent le résultat du traitement en égard à la structure des substrats et aux processus chimiques qui interviennent.

INTRODUCTION

After cellulose, lignin is the most abundant constituent of wood. It accounts for about 25% of the bulk material. Chemically, lignin is an irregular, highly branched, three-dimensional polymer of an amorphous and complex nature. The basic blocks in the polymeric structure are phenylpropanoid units linked together in a variety of different ways, yielding at least ten different types of bonds between the units. The result is a highly complex and unreactive polymer.

There are many unknown aspects related to the structure of lignin mainly because it is practically impossible to isolate it in its native state. Thus, structural features are inferred from derivatives that have undergone changes during the experimental manipulation of the material. However, many important structural features of lignin are known, particularly some related to reactivity modes that are relevant in its degradation, derivatisation and delignification in pulping processes (1,2).

The efficient utilisation of lignocellulosics in biomass processing is mainly limited by its inability to use lignin, although it is recognised that lignin offers a great potential once controlled derivatisation and degradative processes are discovered and implemented. This aspect impacts directly in the production of fuels, and the full use of feedstocks, as well as in the production of chemicals and other higher-value products that may be produced from lignin (1,2).

Although at first sight it would appear that the chemical bleaching of paper pulp is a different problem than the one involved in biomass processing of lignocellulosics, a closer analysis of the chemical issues involved shows that bleaching is just another aspect of the complex problem of

lignin reactivity. Thus, the findings from reactivity studies are relevant and important to a variety of applications of lignin-related areas.

Some of the enzymes that degrade lignin have been identified and isolated only recently. For example, the ligninase from the white-rot fungi Phanerochaete chrysosporium has been isolated and its reaction mechanism studied. Interestingly, the reaction uses hydrogen peroxide to generate an oxy-heme complex that oxidises aryl groups in lignin in single-electron transfer processes. In other words, the reaction proceeds via free radical intermediates, specifically radical cation intermediates that are relatively stable and that decompose when the bond between carbon alpha and carbon beta in the aliphatic chain of the phenylpropanoid unit ruptures. The same chemical bond can be broken in chemically induced oxidations via radical cation intermediates similar or identical to those described in the enzymic reaction (3-7).

Ionising radiation is particularly suited to the production of free radicals. Several studies, including our own, demonstrate the formation of these species in a number of biomass materials where they can take part in ensuing reactions. These reactions may be derivatisations, degradations or polymerisations, depending on the characteristics of the material and the experimental conditions (8-10).

In this paper, we report selected aspects of lignin reactivity linked to radiation-induced phenomena in several materials (wood and certain isolated and treated lignins). Our results demonstrate the importance of free radical processes induced by ionising radiation and allow some of the free radicals involved to be identified.

RESULTS AND DISCUSSION

Although free radicals are observed in wood that has been exposed to light or subjected to certain mechanical stress, green wood does not contain free radicals in large enough quantities to be detectable by Electron Spin Resonance (ESR). However, these species are easily formed in detectable amounts when a suitable amount of energy is absorbed. This energy may be provided by mechanical stress or by electromagnetic radiation, so that free radicals are present in sawdust or in wood exposed to light (11). The stability and fate of these free radicals appears to depend on a variety of factors, including water content (12).

The free radicals detected during the photoirradiation of wood generate broad ESR signals with g-values relatively close to that of a free electron ($g = 2.003$). These free radicals are formed from the cellulosic and lignin components in wood (13).

Our results indicate that the free radicals formed by the effects of ionising radiation on wood appear to be similar to those produced by photoirradiation at wavelengths around 340 nm. However, it is difficult to demonstrate with certainty the correspondence between the radicals induced by the two processes, since free radicals in solid materials generally lead to ESR spectra consisting of broad single peaks. Our ESR results also indicate the presence of free radical species that are extractable with water. These species generate a weak signal and appear to originate from inorganic wood components. A similar situation has been observed when studying the effect of light on Douglas fir, where these weaker signals were also detected (14,15).

The irradiation of Indulin AT and of pyrolised lignin produces an ESR signal typical of phenoxyl radicals. These signals are quite stable and are produced in the presence or absence of oxygen.

Indulin AT shows ESR spectra with a central peak of about 8 to 10 gauss line width. This width is in agreement with the literature data for phenoxyl radicals produced by photoirradiation. However, the signal generated by ionising radiation shows certain hyperfine structure not seen after photoirradiation, which could be the result of several overlapping spectra. This suggests that the initial event in the radiation-induced process is the formation of more than one free radical species. In addition to phenoxyl groups, carbonyl groups and unsaturated carbon-carbon double bonds in the aliphatic chain may generate stable free radicals. For example, the presence of a carbonyl group at the alpha carbon in the aliphatic chain or an unsaturation between the alpha and beta carbons are likely candidates for such radicals. We are studying this problem further.

We have observed that some polymerisation occurs when Indulin AT is irradiated without addition of a solvent. Analysis of the material using Size Exclusion Chromatography shows that the maximum and mean molecular weights increase in comparison with the unirradiated material. Adequate controls show that part of the polymerisation is induced by the heat generated during irradiation; however, the overall effect observed is significantly larger than the effect of heat alone. Similar polymerisation has been produced by the action of acids on lignin (16,17).

Our results suggest that polymerisation predominates at lower doses and in the absence of solvent. As the dose increases, radiolytic degradation begins to predominate. Some of the conditions that determine which process predominates are: type of substrate, presence or absence of solvent or dispersant, type of solvent and radiation dose. Although still not studied, we suspect that factors such as atmosphere and dose-rate may also play a role in the direction that the reaction takes.

The radyolysis of air-saturated tetrahydrofuran produces a characteristic pattern that is easily identified in the mass spectroscopy analysis. Consequently, it is feasible to analyse the irradiation effects on solubilysed lignins in this solvent, provided that possible cross-reactions between the substrate and the solvent are taken into account.

Indulin AT in tetrahydrofuran was irradiated in air at various doses, and the effects of irradiation were analysed by gas chromatography-mass spectroscopy. At a dose of 100 kGy, vanillin and homovanillic acid were identified as radiation products. Many other products were observed from the irradiation of pyrolysed lignin under similar conditions, including 3,4-dimethoxyphenol, p-coumaric acid, vanillin, vanillic acid, zingerone, meconin, 4-(2-propyl)-2,6-dimethoxyphenol and syringaldehyde. As the dose increased to 200 kGy, the effects on the solvent predominated. However, it is still possible to identify some irradiation products, although with less certainty than at a lower irradiation dose.

The degradation of lignin induced by ionising radiation may be understood by assuming that initial free radicals are formed at particular structural features. The most important ones are phenolic hydroxyl groups, the beta carbon in the aliphatic chain in cases when there is an adjacent carbonyl function at the alpha carbon, and unsaturated carbon-carbon bonds in aliphatic sections of the molecule, particularly between alpha and beta carbons. These characteristics are common with those thought necessary for the enzymic degradation of lignin.

Further work is in progress to study of the effects of ionising radiation under different atmospheres, as well as the effects of solvent on the products formed. We expect that the results from these experiments, together with results obtained as the irradiation doses were varied, will help to establish a pathway for an industrial radiolytic processes.

EXPERIMENTAL

Electron Spin Resonance spectra were obtained at room temperature on a Varian V4500-10 A instrument with a 9-inch magnet and a Nicolet data storage system. In the case of wood and sawdust, solid material was used. Other samples were dissolved in either tetrahydrofuran or acetonitrile.

Irradiations were performed in an AECL Gamma Cell 220 and the I-10/1 electron accelerator (18). Samples of wood and sawdust were irradiated as solids, while samples of Indulin AT and pyrolysed lignin were irradiated with or without addition of a solvent. The heat produced during irradiation was measured and considered in the design of adequate experimental controls. In these controls, samples were heated for the time and at the temperature required by the irradiation process, without subjecting the sample to ionising radiation.

High Performance Liquid Chromatography (HPLC) experiments were performed using a Beckman dual pump Model 344, upgraded with a data acquisition system run from an IBM personal computer (Nelson Analytical software 2900 Gel Permeation Chromatography). The system was equipped with Phenomenex columns adequate for use with organic solvents. Although several of these columns are suitable, most of our data were obtained using column 50-1000 mu and tetrahydrofuran degassed with nitrogen at a flow rate of 0.5 mL/min. A 5000A-type guard column was also used. Two detectors were used in series, a UV-visible detector at 220 nm and a fluorescence detector set at 392 nm emission and 278 nm excitation. The calibrations were done using polyethelene standards from Supelco Inc. and the Nelson software mentioned above.

Gas Chromatography-Mass Spectrometry experiments were done on a Hewlett Packard Instrument, GC model 5890 and MS model 5970 with an HP-5 column. Peaks were selected from the gas chromatography spectra and were analysed by mass spectrometry.

Wood chip samples and sawdust were freshly prepared from selected wood specimens. Pyrolysed lignin was a gift from Dr. D. S. Scott. The preparation procedure and specifications of the sample are given in (19). Indulin AT (a type of kraft lignin) was obtained from Westvaco.

Standard analytical procedures for wood followed the methods in the Standard Testing Methods of the Canadian Pulp and Paper Association (20).

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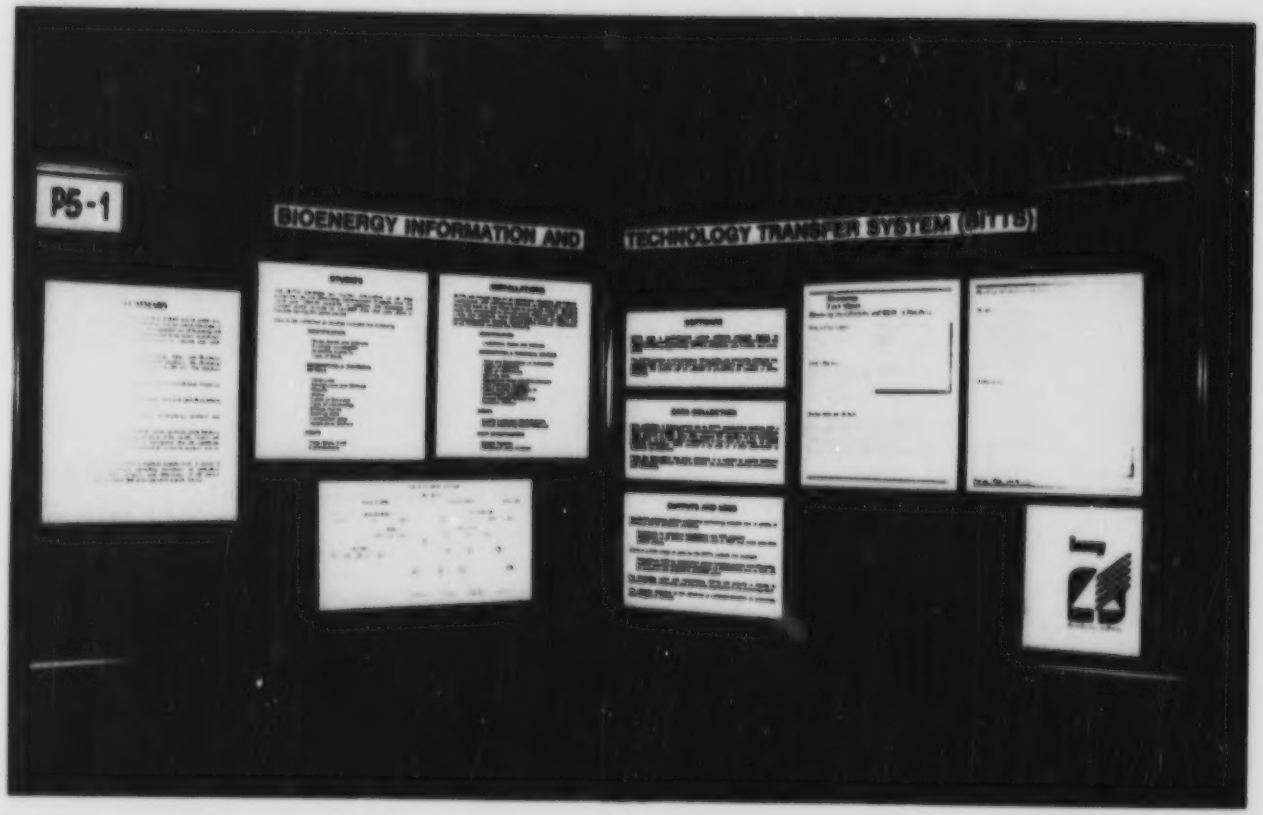
P5-1
BIOENERGY INFORMATION AND
TECHNOLOGY TRANSFER SYSTEM (BITTS)

AN INTRODUCTION TO THE BIOENERGY INFORMATION AND TECHNOLOGY TRANSFER SYSTEM

George Matheson

Marbek Resource Consultants Ltd.

Energy, Mines and Resources Canada is establishing a computerized database, the Bioenergy Information and Technology Transfer System (BITTS).
The database will be a powerful technology transfer tool. A variety of printouts will be available including factsheets on individual installations and R&D projects, and directories of all known installations in Canada and/or that meet specified search criteria.

La Ministère de l'Energie, des Mines et des Resources est en train d'élaborer une base de données informatisée appelée Système de transfert de l'information et de la technologie de bioénergie (désigné par le sigle BITTS - Bioenergy Information and Technology Transfer System).
Cette base de données constituera un puissant outil de transfert technologique. Les données pourront être restituées de diverses façons, y compris sous forme de fiches sur les installations et sur les travaux de R. et D. individuels, et sous forme de répertoires de toutes les installations connues au Canada et/ou des travaux qui répondent à des critères de recherche bien précis.

OVERVIEW OF BITTS

In recent years, substantial federal and federal/provincial funds have been expended in support of bioenergy projects. These initiatives, and the considerable body of activity that has taken place without government support, have produced a vast resource of information.

To date, dissemination of this information has been limited. Accordingly, attention in EMR has shifted to the need for expanded information transfer efforts designed to encourage and facilitate additional bioenergy use in a wide variety of sectors. The benefits of such information transfer activities are expected to be significant.

Indeed, information transfer is a central component of technology transfer, and technology transfer must clearly be at the heart of EMR's bioenergy program. In the current climate of fiscal restraint, downsizing, and non-intervention in the marketplace, information/technology transfer activities are highly cost-effective and important activities - - if not the ultimate raison d'etre for the program as a whole.

Unfortunately, the ability of the department to respond to the information/technology transfer challenge has been inadequate. Accordingly, the Energy Diversity Technology Division of Energy, Mines and Resources Canada (EMR) is developing a computerized information and technology transfer system in support of their mandate of promoting the use of biomass as a form of energy. This system -- the Bioenergy Information and Technology Transfer System (BITTS) -- will be comprised of three main components:

1) INSTALLATIONS (information on non-residential bioenergy installations in Canada)

2) STUDIES (information on bioenergy research and development projects in Canada)

3) CONTACTS (listings of potential bioenergy users plus sources of bioenergy products and expertise).

Work on both the installations and the studies portions of the database is well underway. With the co-operation of facility owners and scientists involved in R&D, it is anticipated that all significant bioenergy installations and all important research projects will be documented on the system.

For installations, the information being collected includes a general description; technical details such as technology, equipment, and performance; and cost data. For R&D projects, the database concentrates on objectives, background, method and results.

The database will be a powerful technology transfer tool. A variety of printouts will be available, including:

- Factsheets on individual installations and R&D projects
- Directories of all known installations and/or R&D that meet specified search criteria.

All printouts will be attractively formatted using page makeup software and a laser printer. The information provided in BITTS will be quality information -- not "as received" information. Moreover, the writing style and descriptive sections will be "publication ready".

There is an almost unlimited range of uses for the BITTS outputs. For example:

- Requests to EMR for information will be handled quickly and efficiently.
- Custom-selected information packages on installations will be prepared and targeted to potential users.
- "Managerial reports" will be produced, aggregating information from selected database fields to provide an overview of bioenergy-related activity in Canada (and how it changes over time).

For bioenergy users and researchers, BITTS will provide a mechanism to showcase their leadership and share their experience in the bioenergy field. For these people and for prospective bioenergy users, BITTS will be a source of valuable information that will help them to maximize the potential benefits available from bioenergy.

In summary, it can be said that the ultimate objective of BITTS is commercialization of bioenergy technologies. This objective is to be achieved by developing a high quality database that will enable EMR (and others) to carry out efficient and effective information and technology transfer activities. Such activities are essential if bioenergy use in Canada is to expand -- and in particular if it is to expand in ways that use the right technology in the right application.

The following sections of this paper provide further details on particular aspects of the BITTS system.

INSTALLATIONS

BITTS is designed to include data on all significant industrial, agricultural, institutional, and commercial facilities in Canada that produce biomass fuels or use these fuels to produce energy. Residential sector installations are not included. Biomass fuels are considered to include wood, wood waste, agricultural crops and residues, food processing wastes, municipal and packaging wastes, sewage, aquatic plants and peat.

Basic information will be collected on each installation in the system. For installations considered to be more important from a technology transfer point of view, additional data will be gathered. In such cases, the information to be collected includes the following:

Identification:
Identification Number
Installation Name
Installation Address
Contact Person

Description & Technical Details:
Description of Installation
Output
Status
Type of Installation
Types of Biomass
Types of Displaced Energy
Type of Technology
Energy Forms Produced (combustion only)
Start-Up Date
Installation Sector and Subsector
Equipment Used
Equipment Displaced
Manufacturer
Rated Capacity of Fuel Handling Equipment
Rated Input Capacity of Conversion Equipment
Rated Output Capacities of Conversion Equipment
Annual Design Biofuel Use
Annual Design Output(s)
Biomass Moisture Content
Fraction of Load Supplied by Biomass
Annual Fuel Displacement
Annual Performance
Equipment Availability
Pollution Control

Costs:
Capital Cost
Non-Capital Costs
Contributions
Annual Operating Costs/Revenue
Fuel Prices

Cost Effectiveness & Job Creation (according to operator):
Incremental Capital Costs
Net Incremental Annual Savings/Revenue
Simple Payback
Permanent Jobs Created

Other:
Operator Comments
Other Information
Summary

STUDIES

The BITTS database will contain information on all R&D supported by the Bioenergy Development Program from the fiscal year 1984-85 onwards. In addition, the database will contain records on non-BDP R&D that took place in Canada during the same period. However, a reduced data collection effort will be applied to the non-BPD R&D during the initial BITTS development process. The result will be BITTS records that will provide useful information, but will not necessarily be "publication ready".

Data to be collected on studies includes the following:

Identification:
Identification Number
Study Name
Study Address
Principal Investigator
Scientific Authority
Type of Study

Description & Technical Details:
Background and Method
Objective
Results
Status
Types of Biomass
Type of Technology
Energy Forms (combustion only)
Start-up Date
Completion Date
Application Sectors

Costs:
Total Study Cost
Contributions

Other:
Principal Investigator Comments
Other Information
Summary

DATA COLLECTION

Data collection is being carried out by BITTS researchers working with a standard questionnaire. The researchers first gather data from files and from other sources at EMR. Next, they contact the operator of the bioenergy installation, or the Principal Investigator in the case of a study, to obtain missing information. Such contact is by mail or, if little information is required, by telephone.

A unique feature of the BITTS data collection system is the use of partially completed, custom questionnaires. The concept is simple: when a questionnaire is mailed out to the owner of an installation for completion, it is already partially filled in with the information that is available from EMR files. This simplifies the job of questionnaire completion for the owner and also provides an opportunity for verification of the information already on hand.

Once the information has been obtained, it is subject to careful technical validation and editorial review to ensure its accuracy, internal consistency, and readability.

SOFTWARE

BITTS uses a sophisticated custom software package (based on Clipper/dBase III Plus) and the computer graphics/form software IPRINT (for output formatting and printing). BITTS is integrated, user-friendly, and menu-driven.

Data input relies on a series of matching questionnaires and data entry screens, with automatic "logic edits" where feasible (to ensure data accuracy). Printed outputs are discussed in more detail below; in addition, BITTS provides on-screen information on installations and studies in response to users' requests.

The BITTS system is fully bilingual. Many fields are inherently bilingual (eg. coded fields); all others are set up as parallel English and French fields (for instance, there are actually two Summary Fields – one English and one French). Similarly, the system will be capable of producing all outputs in either language (except for outputs such as mailing labels that are non-language specific). Data for all records considered important from a technology transfer point of view will be available in both languages.

OUTPUTS

A variety of outputs will be available from the BITTS system. The most important of these are the following:

1. Factsheet

A one or two-sheet summary providing information on a single installation or study. The factsheet is the most important of the BITTS outputs; a sample is presented at the end of this paper. (Note: The sample provides information on BITTS itself.)

2. Directory Reports

A printed list, organized under subheadings, of installations or studies that meet up to 3 specified criteria (menu-driven).

3. Ad Hoc Reports

A printed list of all projects that meet selected searchable criteria not available in the Directory Report menus.

4. Custom Questionnaire

Information from all relevant fields, printed onto a questionnaire.

5. Mailing Labels

Names and addresses for questionnaire recipients and other selected groups of contact persons or Principal Investigators.

6. Mail Merge

Capability to produce individually addressed letters to addresses from the BITTS database.

7. Managerial Reports

Numbers of installations and totals for a given period for several standard categories of installations or studies, presented in chart and graph form.

AVAILABILITY

BITTS is currently under development. Factsheets on a significant number of installations are expected to become available in mid-1989, and the system will be fully operational by the end of the year. Initially, access to the BITTS information will be through EMR, but arrangements to make the data available via other channels are under consideration.

FOR MORE INFORMATION

For more information on BITTS, contact the author, c/o Marbek Resource Consultants Ltd., Suite 407, 2211 Riverside Drive, Ottawa, Ontario, K1H 7X5, or Dr. Bill Lowe, Chief, Technology Planning and Liaison, Energy, Mines and Resources Canada, 580 Booth Street, Ottawa, Ontario, K1A 0E3, (613) 996-2626.

Bioenergy Fact Sheet

STUDIES SERIES

Bioenergy Installations and R&D: A Database

Principal Investigator

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Consultant
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Phone: 613-523-0784 Fax: 613-523-0717

START DATE:	01/88
COMPLETION DATE:	03/89
APPLICABILITY:	
Industrial sector	Agricultural sector
Commercial sector	Institutional sector
TYPE OF BIOMASS:	
Not specific to a type of biomass	
TYPE OF TECHNOLOGY:	
Not specific to a technology	
TOTAL STUDY COST:	$ 190,304 (estimated)

Study Objectives

The overall objective of this study is to improve both the information available regarding bioenergy technology and the efficiency of retrieval of that information. This will be accomplished by the design and implementation of a unique bioenergy database that will include high quality, validated information on bioenergy installations, bioenergy R&D and sources of bioenergy products and expertise in Canada. The database -- known as the Bioenergy Information and Technology Transfer System or BITTS -- will produce the various outputs that will be used to encourage expanded use of appropriate bioenergy technologies. Marbek Resource Consultants Ltd. and Ensyn Engineering Associates Inc., are responsible for conducting this project.

Background and Method

In recent years, substantial federal and federal/provincial funds have been expended in support of bioenergy projects, through incentive programs, demonstration programs, and R&D support. These initiatives have produced a vast resource of information.

To date, dissemination of this information has been limited. Accordingly, attention in Energy, Mines and Resources (EMR) has shifted to the need for expanded technology transfer efforts designed to encourage and facilitate additional bioenergy use in a wide variety of sectors. The benefits of such a technology transfer program are expected to be significant.

The BITTS system will be a key tool in this effort. When complete, it will consist of: (1) Bilingual records on hundreds of installations and studies plus an extended list of sources of products and expertise -- all to be regularly updated, and (2) Customized software capable of producing, for instance, publication-quality factsheets on individual installations and studies; directories of installations and/or R&D meeting specified search criteria; and managerial reports which aggregate and compare data.

In addition to Marbek Resource Consultants and Ensyn Engineering, contributors to the project include the Biomass Energy Institute, Capital Software, and EMR personnel.

(continued overleaf)

Bioenergy Installations and R&D: A Database (continued)

Results

Phase I in the development of BITTS will be complete in March 1989. At that time, most of the major software capabilities will be in place, requiring minor refinement only. In addition, some 200 installations and about 165 R&D projects will be in the system, awaiting finalization. A further 130 R&D projects will also be documented based on a reduced data gathering effort.

The remaining tasks in the development of BITTS are expected to take place in Phase II, scheduled for completion by the end of 1989 (although a wide range of outputs from the system will be available in mid 1989).

Initially at least, access to BITTS will be restricted to authorized users. However, BITTS outputs will be freely available on request, and will be distributed pro-actively by EMR. In the longer term, on-going maintenance of the database by EMR is considered a high priority, to maintain the value of the information provided.

Publications

Sources of outside financial support for this study included:

Source: EMR
Program: BDP
Proj. No: 7-6044
Value: $ 190,304

Scientific Authority: Dr. W.E. Lowe

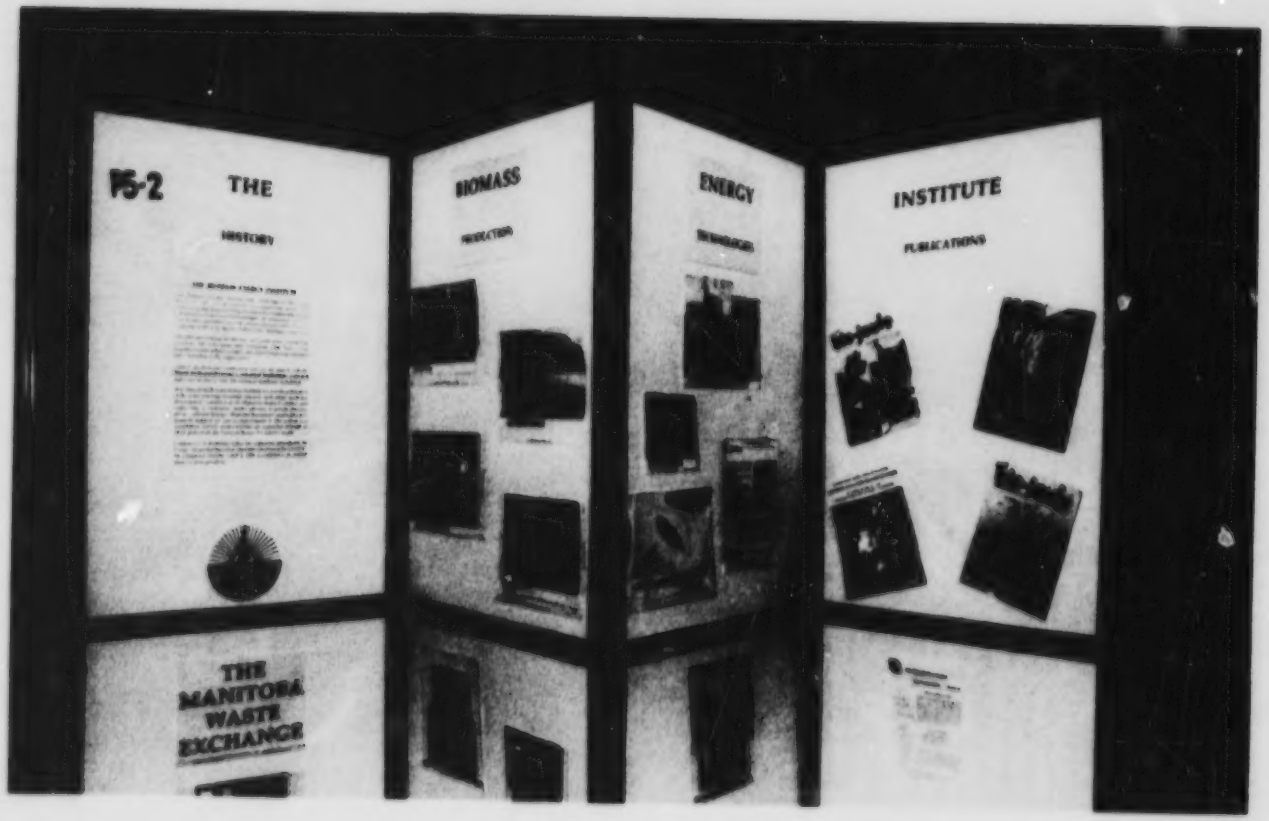
Funding for R&D supported by the Bioenergy Development Program (BDP) was provided by the Interdepartmental Panel on Energy R&D (PERD).

This fact sheet is one of a series. The information has been carefully checked, but has yet to be verified at source. The information is believed to be correct as of:

All fact sheets in this series are prepared using a computerized database, the Bioenergy Information and Technology Transfer System (BITTS).

For further information, contact the Energy Diversity Technology Division of Energy, Mines and Resources Canada, 580 Booth Street, Ottawa, K1A 0E4.

Energy, Mines and Resources


P5-2
THE
HISTORY
BIOMASS
ENERGY
INSTITUTE
PUBLICATIONS
THE
MANITOBA
WASTE
EXCHANGE

BIOENERGY TECHNICAL INFORMATION TRANSFER

V.E. (Beth) Candlish

Biomass Energy Institute Inc.
Winnipeg, Manitoba

The Biomass Energy Institute was established in Winnipeg, March 10, 1971 for the purpose of accumulating, developing, classifying and disseminating information on renewable energy and energy conservation technologies. The Institute is a private, non-profit corporation, and the current chairman of the Board of Directors is Mr. E.A. Speers, INRAD Ltd., Winnipeg, Manitoba.

L'Institut de l'energie biomasse a été fondé à Winnipeg le 10 mars 1971. Le mandat de cet organisme était d'accumuler, de préparer, de classifier et de diffuser de l'information relative aux énergies renouvelables et aux techniques concernant la conservation de l'énergie. L'Institut est une corporation privée à but non lucratif dont le président actuel du conseil d'administration est M. E.A. (Ted) Speers, INRAD Ltd., Winnipeg (Manitoba).

INTRODUCTION

The Biomass Energy Institute was established in Winnipeg, March 10, 1971 for the purpose of accumulating, developing , and disseminating information on renewable energy and energy conservation techniques. The charter members had backgrounds in agriculture and engineering, combined with an enthusiastic concern for good stewardship of Canada's natural resources.

The Institute is a private, non-profit corporation, and the current chairman of the Board of Directors is Mr. E.A.(Ted) Speers, INRAD Ltd., Winnipeg, Manitoba. The Board consists of 15 members, most of whom are located in Winnipeg. At the present time there is one member of the Board from Ontario, one from Saskatchewan, and one from British Columbia. There are six Board meetings annually, one of which is an annual meeting, generally in the fall.

FUNDING

The primary funding for the Institute comes from a membership of about 500. One third of this number reside outside Canada, and all provinces and Territories have members in the organization. There are a number of categories of members. Full members pay the membership fee, which entitle them to receive six issues of the bimonthly bioenergy technology journal, Bio-Joule, and a charitable donation receipt, for those living in Canada. Business members contribute at least $100 to the Institute and receive a business listing in the masthead of Bio-Joule. Corporate members contribute at least $400 and are entitled to twelve copies of Bio-Joule for distribution, and an advertisement, or article, in Bio-Joule each year. Funders contribute at least $1000 per year and are recognized as such in the journal masthead and receive advertising space when requested.

In addition to the financial contributions, the Biomass Energy Institute includes in its membership about 100 exchange publications. Much of our information is gathered through these exchanges with appropriate technology journals. The office space is contributed by Manitoba Research Council and the Institute benefits from other facilities, such as the library and technical services available at the Industrial Technology Centre of the Manitoba Research Council.

Over the years, the Institute library has grown to be one of the largest collections of literature and reports on bioenergy in Canada. The shared facility with the Centre, has three sections of Institute material. In addition we have extensive files on various bioenergy subject areas. Publishers of bioenergy books often send review copies of books to the Institute for review in Bio-Joule. In 1987-88 the value of these books was over $2,000.

ACTIVITIES

Activities of the Biomass Energy Institute involve the publication of Bio-Joule, obtaining contract work in the bioenergy sector, and organizing conferences. The specific activities change with time as the Institute takes advantage of the more popular activities associated with bioenergy. After the formation of the Institute, oil prices began to rise and many activities related to encouraging research in alternative energy technologies flourished, one of which was fuel ethanol from agricultural products.

Public Awareness

In the past few years, as oil prices dropped, and the concern for alternative fuels decreased, the emphasis has been on public awareness of future prospects of the petroleum industry, and encouraging continued bioenergy technology development. Economics are the usual "thorn in the side" of bioenergy technologies. As research and development reduces the costs of bioenergy products, and the by-products are made more adaptable to desirable use, the economics will improve, regardless of the oil prices.

Support for supplements to Bio-Joule have been received from Energy, Mines and Resources Canada, and information transfer responsibilities supported by the National Research Council. As a consequence of the redirection of the IRAP program to emphasize industry contact, Institute staff will be devoting more time to industrial visits involving bioenergy technology development and particular emphasis will be given to environmental and waste concerns.

Waste - to - Energy

Canada has been particularly slow to adapt waste technologies, because of our large land base. The Institute has been involved with various waste to energy projects over the years, and is currently under contract to the Manitoba Hazardous Waste Management Corporation to operate the Manitoba Waste Exchange. The Institute also serves as secretariat for the Recycling Council of Manitoba and manages the Household Hazardous Waste Days during Environment week in June.

Contracts

In the past year the Institute has received contracts to:

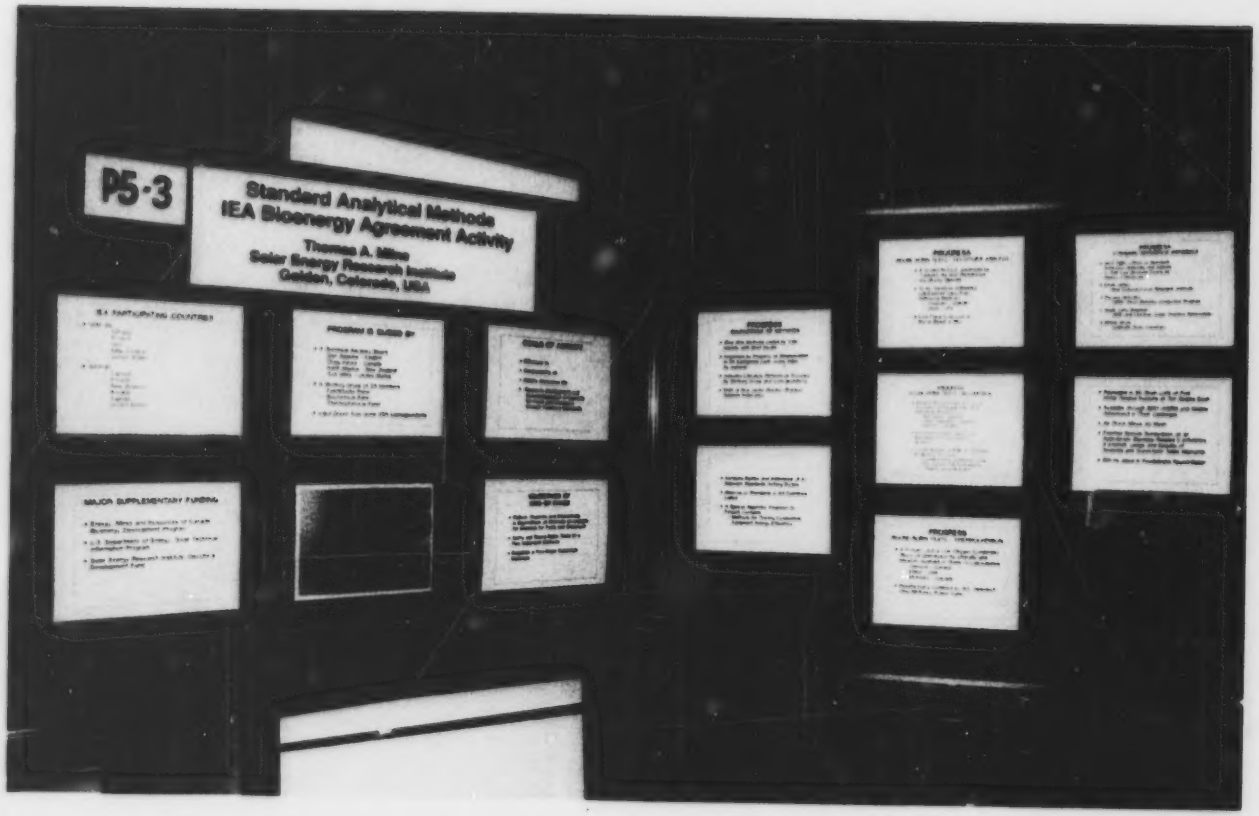
- Participate in a bioenergy information and technology transfer system in cooperation with Marbek Resource Consultants, Ottawa
- Provide publication and report writing support for comparison of propane and straw as heat source for grain drying, in cooperation with the Prairie Agricultural Machinery Institute at Portage la Prairie Manitoba
- Conduct a seminar and prepare reference material on energy savings on the farm
- Organize a conference on Alcohol Fuels for Transportation.

Conferences

Conferences in bioenergy topics are supported periodically by Energy, Mines and Resources Canada. In 1986 the Institute cooperated with the Solar Energy Society of Canada to organize the Renewable Energy Conference '86 in Winnipeg. The most recent conference organized by the Institute was the CANPAC '88 (Canadian Power Alcohol Conference), Alcohol Fuels for Transportation held on October 3 and 4, 1988 in Winnipeg. Several conferences had been held in the early eighties on the same subject.

CONCLUSION

The recent purchase of a display will allow Institute staff to use the display in public areas, and at conferences, to illustrate bioenergy technologies, and encourage support for the activities of the Institute. The past few years have been difficult for bioenergy technology research and development funding, and encouraging public support for these technologies. The support of the Biomass Energy Institute during these difficult times is much appreciated.


P5-3
Standard Analytical Methods
IEA Bioenergy Agreement Activity
Thomas A. Milne
Solar Energy Research Institute
Golden, Colorado, USA
MAJOR SUPPLEMENTARY FUNDING

METHODS OF ANALYSIS OF BIOMASS FOR FUELS AND CHEMICALS

T. A. Milne and H. L. Chum

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Golden, Colorado 80401, USA

This paper will summarize the accomplishments of a recently completed first phase of a program sponsored by the International Energy Agency Bioenergy Agreement. Member countries in 1988 were Canada, Finland, Italy, New Zealand and the United States. Energy, Mines and Resources of Canada and the U.S. Department of Energy contributed substantial supplementary funding to permit a broadened scope of activity. Three major activities will be summarized:

(1) The first edition of a loose-leaf, updatable Sourcebook of Methods of Analysis for Biomass for Fuels and Chemicals.
(2) The status and reported results of three round-robin tests of methods: a) a test of an enzymatic digestibility protocol using standard substrate and enzymes. A protein analysis, using a common BSA sample was also part of this test; b) measurements of moisture and ultimate analysis of a low and high-pressure pyrolysis oil, using methods of the laboratory's choice; c) analysis of four-five representative lignocellulosics using a new protocol developed by O. Theander.
(3) The plans for establishment of four-five lignocellulosics (woody and herbaceous) in the Standard Reference Material System of the National Institute of Standards and Technology (formerly the National Bureau of Standards).

Cette communication affichée résumera les réalisations de la premiére phase récemment terminée d'un programme parrainé dans le cadre de l'accord sur la bioénergie de l'Agence internationale de l'énergie. En 1988, les pays membres de cet organisme étaient le Canada, la Finlande, l'Italie, la Nouvelle-Zélande et les États-Unis. Énergie, Mines et Resources Canada et le Department of Energy des É.-U. ont fourni un financement supplémentaire substantiel pour élargir le spectre des activités. Les trois principales activités suivantes seront résumées:
(1) La premiére édition de Sourcebook of Methods of Analysis for Biomass for Fuels and Chemicals, manuel á feuilles mobiles, pouvant étre mis á jour.
(2) L'avancement de trois essais comparatifs inter-laboratoires portant sur les méthodes suivantes et les résultats obtenus: a) essai d'un protocole de digestibilité enzymatique á l'aide d'un substrat standard et d'enzymes. Cet essai comportait également une analyse des protéines, basée sur en échantillon commun de BSA; b) des mesures de l'humidité et l'analyse ultime d'huile obtenue par pyrolyse á faible pression et á haute pression, le choix des méthodes étant laissé aux laboratoires; c) analyse de quatre ou cinq produits lignocellulosiques représentatifs au moyen d'un nouveau protocole mis au point par 0. Theander.
(3) Les plans de mise au point de quatre ou cing produits lignocellulosiques (ligneux et herbacés) á inclure dans le Standard Reference Material System du National Institute of Standards and Technology (autrefois le National Bureau of Standards).

INTRODUCTION

The earth has a huge diversity of biomass feedstocks, including trees, crops, liquid and solid municipal wastes, oil-producing plants, waste wood, and agricultural residues. Today's options for converting these feedstocks range from direct burning for heat and electricity to thermochemical and biochemical processes for making liquid fuels and chemicals. These processes, combined with sensible management of the biomass resource, can be part of the solution to the world's energy supply and environmental problems.

Scientists and engineers have made great progress from the first generation conversion technology available 15 to 20 years ago. Similar advances have taken place in analytical techniques and equipment. There is a growing consensus that establishing standard methods for analyzing biomass and its conversion products would speed research and improve its quality.

Several groups and nations have shown interest in establishing biomass standards. A 1984 workshop (1) organized by the Solar Energy Research Institute (SERI) and supported by the U.S. National Bureau of Standards

(NBS, now National Institute of Standards and Technology, NIST), the Pacific Northwest Laboratory (PNL), Oak Ridge National Laboratory (ORNL), the National Research Council of Canada, the International Energy Agency (IEA) and the National Science Foundation (NSF) was a major step in discussing and formulating the need for standards. The American Society for Tests and Measurements has expressed strong interest in ultimately issuing new biomass-related standards. (2) Energy, Mines, and Resources (E,M&R) of Canada is pursuing the issue as well, by establishing standard materials or feedstocks for conversion research and by coordinating common analyses of pyrolysis oils and enzymatic assays. (3,4)

In 1986, the International Energy Agency (IEA) began an activity (5) to start to address the need for voluntary standards. Sponsored initially by Canada, Finland, New Zealand, and the United States, with Italy joining in 1988, the program has three tasks: 1) to carry out selected analysis comparisons between laboratories, 2) to establish standard reference materials for both woody and herbaceous plants, and 3) to assemble a sourcebook of relevant analytical methods and standards now being used by laboratories and industry. Energy, Mines and Resources and the U.S. Department of Energy have provided major supplementary funding.

The IEA standards activity has benefitted from the contributions of many scientists from around the world. An International Advisory Board has provided broad guidance to the program. A Working Group of about 30 scientists was established in 1987 to help plan and conduct specific activities. Another 250 scientists (correspondents) have received regular information on the project and many have contributed methods for the sourcebook or are participating in round robins.

ACTIVITY GOALS AND OBJECTIVES

The goals of this activity are to provide efficiency in, comparability of, and quality assurance for research, development and commercialization of biomass for fuels and chemicals. The focus is on voluntary analytical standards and methodology. The scope includes feedstocks, conversion measurements and intermediates, and properties and performance of final fuel or chemical products.

The objectives of the activity are to: collect, organize and disseminate a sourcebook of methods of analysis for biomass for fuels and chemicals; carry out round robin tests of a few important methods; and establish a few major reference materials.

RESULTS

Preparation of the sourcebook (6) has been the major task within the IEA activity. Methods selected were primarily those adopted as voluntary standards by private associations. A number of literature citations are included as well. These represent newer instrumental methods and those relevant to conversion processes such as fermentation and pyrolysis.

Standards specific to biomass energy exist in only a few cases, for example, municipal solid waste and wood fuels. Most of the standard methods come from related industries such as pulp and paper, agriculture, and fossil fuels. In fact, many biomass researchers have adopted these methods as interim standards. However, the applicability to biomass of some of these is limited, as is noted in the literature.

Sourcebook

Each section of the sourcebook includes citations of standard methods and literature methods, differentiated by paper color (white for standards, green for literature). The sourcebook lists only citations and abstract citations provided by the sources (where available) to save space and abide by copyright limitations. Citations include information on availability. Complete addresses of sources of standards are provided in an Appendix. Reports on other phases of the IEA Standards Activity are also included in the Appendices. These include a special report on small combustor efficiency prepared by Finland; reports on the round-robin tests; recommendations on selection of standard reference materials; a list of additional sources of information; and a glossary of terms related to biomass.

Over 800 methods are listed by title, with brief abstract where available. The methods are generally organized by property measured, with a cross-index by material. The Categories are as follows:

- Sampling and Preparation of Feedstocks
- Physical and Thermal Properties
  - Density and Specific Gravity
  - Particle Size Determination and Sieving
  - Pore Size and Capacity
  - Heats of Combustion
  - Thermal Properties
- Elemental Analyses
  - Ultimate Analysis
  - Oxygen
  - Nitrogen
  - Sulfur
  - Halogens
  - Metals and Other Inorganics
- Chemical Component and Group Analyses
  - Proximate Analysis
  - Moisture
  - Ash, Dirt, and Inorganics
  - Cellulose and Holocellulose
  - Hemicelluloses
  - Lignins
  - Extractives
  - Functional Groups and Compounds Classes
  - Sugars and Other Carbohydrates
  - Proteins
- Special Categories and Biomass Materials
  - Forage
  - Microalgae
  - Oilseeds
  - Peat
  - Miscellaneous Biomass
- Fuel Product Analyses
  - Solid Fuels
  - Petroleum-derived Liquid Fuels
  - Lignocellulosic and Oxygenated Liquid Fuels
  - Gaseous Fuels
  - Non-fuel Products
- Waste Product Analyses
  - Solid Waste
  - Liquid Waste
  - Atmospheric Analysis
- Conversion System Performance and Specifications
  - Combustion

Gasification
Pyrolysis and Liquefaction
Bioconversion
Enzymatic Assays
Fire and Flammability
Measurements, Units, Quality Assurance, and Round-robin Tests
Temperature, Pressure, and Flow
Chromatography
Spectrometry

We recognize that the collection of citations in the sourcebook is far from complete and covers predominantly U.S. standards. We hope that those who use the sourcebook will suggest additional methods, comment on limitations of those included, and provide feedback on the usefulness of the publication. The IEA Voluntary Standards Activity will continue through 1991 to allow continuation of round-robin tests and expansion of the sourcebook. In particular, the literature portion of each method category contain only a few representative citations and could be greatly expanded.

Round Robin Tests

An integral part of the IEA Voluntary Standards activity has been the planning and execution of round-robin tests of particularly critical methods. At the Working Group meeting in Denver in 1987 (7) each of three subpanels made recommendations for initiation, or continuation, of round-robin testing.

The biochemical panel of the standards working group laid plans to complete a round-robin assay of enzymatic hydrolysis of a pure cellulose, using common enzymes and cellulose and an assay procedure developed by Hermann Esterbauer University of Graz) (8). In addition, a common protein (bovine serum albumin - BSA) was distributed by Karel Grohmann (SERI) so that each laboratory could analyze the enzymes and BSA by the methods they normally use. The general plan and progress has been described by Barbel Hahn-Hagerdahl (University of Lund) (10).

This round-robin is an augmentation of efforts begun several years ago by another IEA activity (CPD-2), and is continuing largely under the new IEA activity in bioconversion led by Jack Saddler (Forintek) (see paper, this proceedings). The enzymatic hydrolysis results from some ten laboratories are being submitted to the journal Biomass (12).

The thermochemical panel of the standards working group recommended a round-robin test of pyrolysis/liquefaction oils for moisture and ultimate analysis (with direct oxygen determination when possible), using the methods ordinarily used in each laboratory. This round-robin is being coordinated by Jim McKinley (BC Research) (13), Ralph Overend (NRCC) and Doug Elliott (Pacific Northwest Laboratories).

Two samples of pyrolysis/liquefaction oils from wood were distributed to participating laboratories in October 1988. Sample 1 was a Waterloo Fast Pyrolysis process oil. Sample 2 was a PERC process oil from the U.S. Department of Energy's Biomass Liquefaction Experimental Facility.

The samples have been analyzed by the procedures normally used in the participant's laboratory. The results appear elsewhere in this proceedings.

The feedstocks panel of the standards working group elected to test a new protocol for analyzing both woody and herbaceous species (14).

The feedstocks analysis comparison is being coordinated by Olof Theander (Swedish Agricultural University) and Helena Chum (SERI). Theander is finalizing his protocol, while Keith Mackie and Peter Dare (Forest Research Institute of New Zealand) and Jack Ranney and Janet Cushman (Oak Ridge National Laboratory) will supply the woody species (Pinus radiata and Populus deltoides) and Colorado State University (James Linden) and the Hawaii Natural Energy Institute (Vic Phillips) and the Hawaiian Sugar Planters Association (K. K. Wu) will supply representative wheat straw and bagasse samples. These samples will be an addition to the research materials collection of the NIST (NBS) Office of Standard Reference Materials (Stan Rasberry, Bill Reed, Bob Alvarez, Tom Gills and Eugene Domalski). A fifth sample, sweet sorghum, was recommended for testing. However, frozen and forced-air dried samples of freshly harvested samples supplied by Jerry Cherney of Purdue University (as part of Janet Cushman's herbaceous species program at ORNL), were analyzed by Lundgren and Theander at Uppsala. The results showed such great losses of some carbohydrates on drying that the utility of maintaining a dried reference sorghum is questionable. As soon as materials and protocols for these round-robins are finalized, a solicitation of cooperating laboratories will be made.

Please contact T. A. Milne if you wish to participate in any of the round-robin tests.

Reference Biomass Materials

There exist few, if any, publicly available standard reference materials (SRM's) representing major biomass feedstocks (1). The National Institute of Standards and Technology's (NIST) Office of Standard Reference Materials (OSRM) maintains a few SRM's of plant materials, but these are mainly certified for inorganic trace materials (15). TAPPI formerly had some standard pulps, but these are no longer available. Individual government programs and laboratories have maintained supplies of wood chips or powdered wood for their own analytical use and for use by their subcontractors (e.g. National Research Council of Canada; Energy, Mines and Resources of Canada; Forest Products Research Laboratory of the U.S. Department of Agriculture). However, these are not generally available.

It has been a goal of the IEA activity, and was a major recommendation of the voluntary standards working group (16), that a bare minimum of typical biomass materials be obtained and made available for round-robin tests and analytical quality control. The materials recommended were: Pinus radiata (without bark), Populus deltoides (with bark), wheat straw, sugar-cane bagasse and sweet sorghum. (Subsequent tests of sweet sorghum showed such alternation on drying that it has been dropped from the list as impractical to maintain in a representative form for several years).

Negotiations have been completed with NIST-OSRM to prepare, package, maintain, list, and sell 50g lots of these

materials (in 10g mylar-sealed packets). It is planned that these will be available for the round-robin testing discussed above and for use by many laboratories in both analytical method testing and small-scale conversion tests. As studies are made on these materials, a data base on their varied properties will emerge and can be reported in the future, perhaps at a special session of a biomass meeting.

CONCLUSIONS

A significant collection of methods of analysis for biomass for fuels and chemicals has been compiled, though it is by no means complete. The Solar Technical Information Program of DOE/SERI plans to publish the first addition in loose-leaf form in the fall of 1989.

During the second phase of this IEA activity (1989-1991), supported by Canada, Finland, New Zealand, Norway, Sweden and the United States, methods and literature references will be added to the Sourcebook; the round-robin tests of feedstocks and thermochemical conversion products will be continued; and consideration of addition of more research materials will be given, e.g. a milled-wood lignin and a xylan.

Interested readers are invited to contact the authors at SERI for further information about these activities.

ACKNOWLEDGEMENTS

The authors express their thanks to the IEA participating countries, Energy, Mines and Resources of Canada, the USDOE Solar Technical Information Program, and the SERI Director's Development Fund for providing funding for this activity. Thanks is also expressed to the many professional colleagues who guided and assisted the program, including the technical advisory board, the working group, the correspondents, the NIST staff, the providers of research materials and the round-robin organizers and participants, many of whom are mentioned above.

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8) Esterbauer, H., University of Graz, Schubertstr. 1, A-8010, Graz, Austria.

9) Grohmann, K., Bioconversion Research Branch, Solar Energy Research Institute, 1617 Cole Boulevard, Golden, CO 80401.

10) Hahn-Hagerdahl, B., Chemical Centre, Department Tech. Microbiology, P.O. Box 740, S-220 07, Lund, Sweden.

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14) Theander, O. University of Agricultural Science, Uppsala, Sweden.

15) Seward, R. W., editor. NBS Standard Reference Materials Catalog 1988-89. NBS Special Publication 260. Gaithersburg, MD: National Institute of Standards and Technology. January, 1988. (Samples of citrus leaves, tomato leaves, pine needles, corn stalks, and corn kernels, certified for a large number of inorganic elements, are available.)

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A STANDARD METHODOLOGY FOR
ESTIMATING THE COST PERFORMANCE
AND ECONOMIC VIABILITY OF RENEWABLE
ENERGY TECHNOLOGY APPLICATIONS
RESULTS
PS-5

A STANDARD METHODOLOGY FOR ESTIMATING THE COST, PERFORMANCE AND ECONOMIC VIABILITY OF RENEWABLE ENERGY TECHNOLOGY APPLICATIONS

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An International Workshop on the Economics of Renewable Energy Technologies was held to reach agreement among IEA member countries on a standard format, set of parameters, and methodology which described the relevant cost and performance factors, and appropriate approach to analysing the economics of, renewable energy technology applications. The planning process, Workshop and follow-up activities have been successful in meeting the objectives established for this effort. An International Energy Agency document is expected to be published later this year.

Un atelier international sur "L'économie des technologies de l'énergie renouvelable" avait lieu afin d'en arriver à une entente entre pays membres de l'AIÉ sur un format uniforme, un ensemble de paramètres, une méthodologie qui décrit les facteurs pertinents de coûts et de performance et une approche adéquate afin de faire l'analyse économique des applications associées aux technologies de l'énergies renouvelable. Le processus de planification, l'atelier et les activités de suivi ont contribué au succès de cette entreprise. Un rapport publié par l'AIÉ est attendu cette année.

INTRODUCTION

Under the auspices of the Renewable Energy Working Party of the International Energy Agency, Energy, Mines and Resources Canada hosted a Workshop on the Economics of Renewable Energy Technologies (WERET) at Le Chateau Montebello, Montebello, Quebec, from October 18-21, 1987. The Workshop was the culmination of an intensive six month planning effort directed at developing:

1) Technology cost and performance factor formats (CPFF's) for each of eight renewable energy technologies (RET's);
2) Sector methodology and economic analysis formats (SMAF's) for each of three application sectors.

RESULTS

Introduction to Workshop Objectives and Structure

An Organising Committee (OC) was established to oversee the planning process for this Workshop. At a meeting in Athens in April 1987, the Workshop approach was discussed. Agreement was reached on a set of objectives (Table 1). Key Experts (KE) were nominated by IEA member countries to carry out the required preparatory work for 8 technologies and 3 application sectors (Table 2). Canada provided the biomass and small hydro technology experts, and the author was technical coordinator for the Workshop planning effort.

In preparation for this Workshop, a detailed planning schedule was developed and followed, guiding the technology and sector experts through the process of defining the relevant items to be included in the cost factor formats. A case study approach was followed to assist in defining the costs of RET's.

Table 1

OBJECTIVES - ACCOMPLISHMENTS

1. To define the factors that determine the cost of energy from select renewable energy technologies (RET's).
   - Prepared Cost/Performance Factor Formats (CPFF's) for eight RET's.
2. To establish recommended guidelines for economic analysis methodologies used to calculate the cost of energy from RET's, from both national and private investor perspectives in selected sectoral applications.
   - Prepared Sector Methodology/ Analysis Formats (SMAF's) for three selected sectors.
     (Analysis of national perspective dealt with in separate special topics paper).
3. To better understand the effect of variations in key analytic, cost, resource and technology performance assumptions and parameters on the cost of energy from RET's.
   - Sensitivity analysis parameters specified for several technologies.
   - Some country comparisons of data for selected case study examples.
4. To identify and compile in bibliographic form a list of highly regarded economic analyses, studies and papers.
   - Some information available.
5. To assess the effect of variations in key technical and economic factors on the economic viability of RET's in IEA member countries.
   (Not addressed but methodology gives capability in case study approach).

Table 2

Key Technology Experts

WIND	Mr. P. Northorst RISO National Laboratory Roskilde, Denmark
PASSIVE SOLAR	Mr. J. Meikle Davis, Belfield & Everest London, England
SOLAR THERMAL	Mr. F. Sanchez CIEMAT - IER Madrid, Spain
PHOTO-VOLTAICS	Dr. A. Raeuber Institute for Solar Energy Systems Freiburg, West Germany
BIOMASS	Mr. W. Edwards B.H. Levelton & Assoc. Ltd. Vancouver, B.C., Canada
GEO-THERMAL	Mr. M. Yoshikai Sunshine Project, MITI Tokyo, Japan
ACTIVE SOLAR	Mr. W. Short Solar Energy Research Institute Golden, Colorado, U.S.
SMALL HYDRO	Mr. R. Hutt Washburn & Gillis Associates Ltd. Fredericton, N.B., Canada

Key Sector Experts

INDUSTRY	Mr. W. Mebane ENEA - CASACCIA, Rome, Italy
BUILDING	Mr. B. Diczfalusy SPK, Stockholm, Sweden
UTILITY	Mr. P. Bos Polydyne, Inc., San Mateo, CA, U.S.

Cost/Performance Factor Formats

The approach agreed to at the Athens meeting was to develop cost/performance factor formats (CPFF's) for each technology. As Technical Coordinator, the author worked with the technology experts in an iterative process to develop the CPFF's. Through this iterative process, a standardized set of section headings were developed along with a set of content guidelines. Analysis conventions were established for base year for cost estimates and in-service year.

The purpose of the CPFF's was to describe factors which define the cost and approach to costing and analysing renewable energy systems. The CPFF's explicitly itemize all of the relevant capital and operating cost, resource characteristics, technology performance, and energy demand characteristics which define a RET application.

In the process of developing these formats, a number of definitional and related problems were encountered. The most important issue was the recognition of the need to explicitly include resource characteristics and technology performance parameters in the formats.

These CPFF's have been applied to develop examples for a selected set of technology applications. A total of 21 'case study' examples were selected as being representative of the most common applications of RET's either in use today or in advanced stages of development. In addition to the biomass and small hydro examples, 11 examples were developed for applications of other RET's in Canada. A concluding section of the CPFF's lists economic analysis parameters as a logical interface with the SMAF's.

Sector Methodology/Analysis Formats

The SMAF's were developed to illustrate the appropriate methodology to calculate economic and financial viability. The 3 Sector experts pursued a parallel path to develop formats to specify the relevants factors required to conduct an analysis of RET applications, and to be tested through analysis of the case study examples.

A consistent set of Economic Analysis Parameters were developed, along with a set of guidelines for selecting appropriate analysis assumptions. The treatment of various parameters such as IDC, Depreciation and Working Capital proved difficult, but were resolved in a preparatory meeting.

The Sector formats take specified input data from the CPFF's and follow a standardized methodology to calculate selected indicators for technology cost/performance and economic viability. A discounted cashflow methodology is common for all of the sectors, although different indicators are generally used.

Each of the methodologies were developed using a spreadsheet analysis program. The RETA 123 program discussed in a companion paper duplicates the methodology used in these programs, although the utility sector methodology also employs a more sophistical required revenue analysis approach. Table 3 summarized the analysis conventions and selected indicators for the sector methodologies.

Table 3

GUIDELINES FOR KEY SECTOR EXPERTS

NATIONAL (Social or Public)
- Costs/values measured net of all taxes
- Real(constant) currency units
- Real(net of inflation) price escalation
- Real national discount rates (opportunity cost of capital before taxes)

INVESTOR (Private)
- Sector specific methodology
- Explicit account of fiscal effects (taxes and rates, credits, subsidies, depreciation)
- Real cost of capital(nominal analysis)
- Specified ratios for debt/equity/shares

Calculation Methodology

Discounted Cash Flow(DCF) Analysis
Construction completed in Year 0
Operation commences in Year 1
Project lifetime of 20 years
Costs/prices in 1986 currency units(mid-year)
Real price escalation factors
Present Value(PV)/Discounted Sums(DS)
- calculated to 1986

Measurement Units

Own country currency(U.S.$ conversion factors)
Metric units for physical quantities
Heat input/output in joules; electricity in kwh
Own country discount(interest) and tax rates

Constant Parameters

National discount rate	- 5% real
Utility discount rate	- 5% real(after tax)
Industry discount rate	- 10% real(after tax)
Nominal inflation	- 5% per year
Real price escalation	- 0 (non-energy)
Crude Oil Price	- $18/barrel U.S.(1986)
Oil product prices	- Margin over crude oil
Natural Gas Price	- 85%/oil product prices
Electricity Prices	- IEA electricity study
Energy price increases	- Oil/Gas at 2%/yr Coal at 1%/yr

Cost/Viability Indicators

COST -	Levelized energy price per unit of energy produced (PV of costs/DS of energy produced)
VIABILITY -	Net Present Value(NPV) Internal Rate of Return(IRR) Required Revenue(regulated utility)

Special Topics

In addition to the development of the CPFF's and SMAF's, part of the Workshop focused on a number of special topics related to the economic analysis of RET's. The topics and the focus or conclusions of the discussions were:

a) Public Analysis Perspective

A presentation with panel discussion examined the reasons for the differences in parameters between the public and private analysis perspectives. Key differences were identified in discount rate, time frame and the evaluation of inputs and outputs. It was agreed that the SMAF's would focus on assessing financial feasibility, rather than attempting to adjust all relevant parameters to reflect public or social evaluations.

b) Factors Affecting Economic Viability

A presentation introduced alternative approaches to technology costing based on weight measurement - 'When in doubt, weight it!'.

Another presentation discussed the various considerations for introducing RET's into developing countries. One key requirement is technologies that are relatively simple to maintain and operate. Access to capital or favorable financing terms is also important for RET's which tend to be capital intensive.

c) Utility Planning Perspective

A panel discussion on electric utility planning considerations in IEA member countries focused on the issues surrounding the introduction of RET's within the utility system. The analysis of these systems is complicated by factors such as variation in output different from the utility load curve, and reliability or capacity factors.

d) Technology Forecasting

Several presentations examined various approaches to forecasting the future cost/performance of RET's. These included projects undertaken by the California Energy Commission and the U.K. Department of Energy. Examining the role of RET's was an important feature of these studies.

DISCUSSION

The CPFF's explicitly itemize all of the relevant capital and operating cost, resource characteristics, technology performance, and energy demand characteristics which define a renewable energy technology application. A concluding section of the CPFF's lists economic analysis parameters as a logical interface with the SMAF's.

The SMAF's were developed to illustrate the appropriate methodology to calculate economic and financial viability. The formats were used to develop a total of 21 illustrative examples of renewable energy technology applications across IEA member countries. A total of 17 examples were developed for Canada, including 6 biomass technology applications. These examples are being analysed in a forthcoming paper to be presented at the June 1989 annual conference of the Solar Energy Society of Canada (SESCI).

The CPFF's and SMAF's developed for the Workshop are being compiled and edited into a form suitable for publication in an IEA document: "Recommended Guidelines for Estimating the Cost, Performance and Economic Viability of Renewable Energy Technology Applications". This document will be published later this year.

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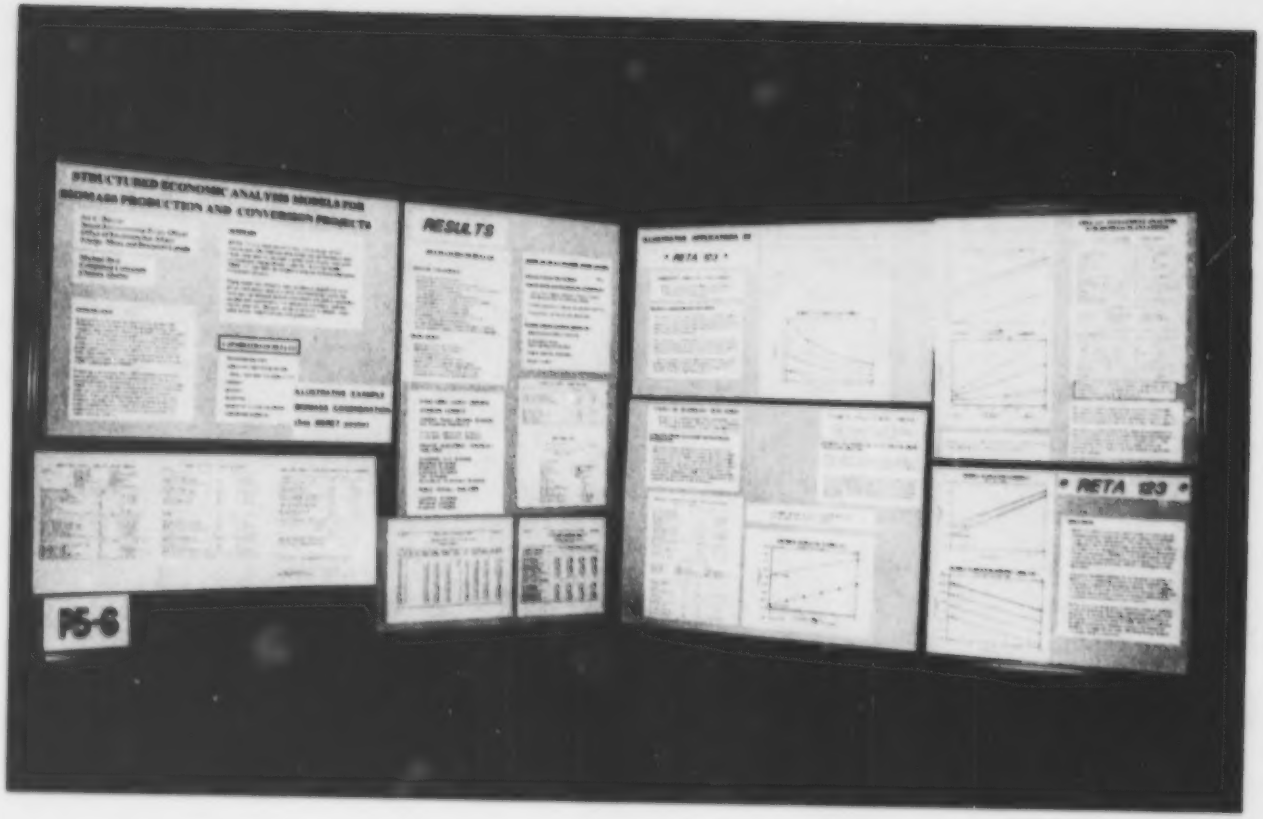
RESULTS
RETA 93
RETA 93
F5-6

STRUCTURED ECONOMIC ANALYSIS MODELS FOR BIOMASS PRODUCTION AND CONVERSION PROJECTS

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Two economic analysis models have been developed for renewable energy technology applications. RETA 123 is a menu-driven Lotus 123 template which manipulates specified and structured cost, performance and value input data to calculate a series of economic indicators. A similar model, TREE 123, analyses biomass plantation investment projects. These models are versatile project and policy analysis tools suitable for feasibility level analysis. They incorporate useful features such as separate private investment and public analyses, tax and debt parameters, cost and price schedules, and sensitivity analyses. Results can be displayed in tabular, structured project report formats and graphically.

Deux modèles d'analyse économique ont été developpés dans le cas d'applications reliées aux technologies de l'énergie renouvelable. RETA 123 est un modèle Lotus 123, piloté par menus, qui manipule des données d'entrée, qu'il s'agisse de données de coût spécifiées et structurées, de performance et de valeur. Un modèle similaire, le TREE 123, analyse les projets d'investissements dans les plantations énergétiques. Ces modèles sont versatiles, d'opération facile, et constituent des outils d'analyse de projet et de politique applicables au niveau de faisabilité qui incorporent des charactéristiques utiles telles que des capacités d'analyse distinctes d'investissement privé et public, des paramètres de taxes et de dettes, des listes de coûts et de prix, et des analyses de sensibilités. Les résultats peuvent être présentés sous forme de tableaux, de graphiques ou de rapports de projet.

INTRODUCTION

In parallel with the planning effort for the October 1987 Workshop on the Economics of Renewable Energy Technologies (WERET -see companion paper on this topic), a menu controlled, Lotus 123 template named RETA 123 was developed. RETA 123 is an versatile tool for conducting feasibility level analysis of project proposals to fulfil policy, program and project analysis requirements. RETA 123 contains a structured input format which is set up to be consistent with the data entries included in the cost performance factor formats (CPFF's) developed for WERET.

Following a preliminary May 1988 workshop on technical and economic considerations influencing the viability of biomass plantation investments, a similar Lotus 123 template, TREE 123, was developed to analyse the factors which determine the economic viability of short rotation intensive forestry. These two models have been tested and are now available for wider use. The features of these models and some illustrative results of analyses conducted to date are presented to demonstrate their versatility and possible application.

RESULTS

Capabilities of RETA 123

RETA 123 is a versatile tool for conducting feasibility level economic and financial analysis of project proposals to fulfil policy, program and project analysis requirements. RETA 123 contains a structured input format which is consistent with the data entries included in the cost performance factor formats (CPFF's) developed for WERET. The model has 7 distinct input screens: labels/constant parameters, capital, expense, revenue, incentives, 1-variable and 2-variable sensitivity analysis. Assumptions, cost and value data can be specified separately for social and financial analysis purposes. As well, selected annual quantities, prices and values can be varied using a USER-defined schedule feature.

RETA 123 manipulates the input data to perform simultaneous discounted cashflow analyses from both the public (economic) and private (financial) analysis perspectives, and generates a specified set of output indicators which are consistent with the calculations performed in each of the sector methodology analysis formats (SMAF's) developed for the Workshop. In addition, the model includes structured output report formats for project summary, cashflow, investment, expense, revenue and

income tax. The model is capable of analyzing tax system and incentive effects, and can display the results in tabular and graphic form.

Key Features of RETA 123

RETA 123 combines analytic convenience and functional design to provide an extremely versatile analytic tool. All relevant input parameters are included. Separate base, discount and in-service years, and separate private and public input cost and value parameters can be specified. Capital Cost can be scheduled over a 3-year period, and debt and depreciation factors are included. Tax and inflation rate assumptions are included in constant parameters, and multiple expense and revenue categories include constant factors for real price change.

The model design incorporates features such as macro-driven file save and retrieve, operation in menu-driven mode, single Screen input schedules, VIEW mode for examining results, PRINT macro for input and output reports, automated use of Lotus 123 GRAPH function, and access to all Lotus 123 functions for file editing. RETA 123 has been tested and verified and is available on disk from the author. Two versions are available, one for conducting both private and public analyses, the second in streamlined form for conducting only financial analyses. A complete users manual is also available.

Potential Applications of RETA 123

1. Sensitivity Analysis for Policy Development Purposes

The 1 and 2-variable sensitivity analysis capability of RETA 123 can be used to analyse the effect on project returns of changes in variables that might be influenced by government policy. For example, these analyses could be used to examine the effect of variations in output value or of changes in tax incentives which might arise due to purchase policy or incentives.

Figure 1 illustrates the sensitivity of project net present value (vertical axis) to variations in the discount rate (horizontal axis) and the expected selling price for cogenerated electricity from biomass. The data are drawn from a Canadian case study example prepared for WERET. Given the assumed cost and other input data for this example project, including Class 34 capital cost allowance, the graph illustrates the importance of maximizing the value of output electricity in order to improve the viability of biomass cogeneration projects.

2. Current vs. Future Technology Comparison

The report formats and sensitivity analysis capability of RETA 123 can also be used to examine the effect on relative economic returns of changes in output values and changing technology over time. The data for this example are based on a recent study completed for EMR on Iogen's ethanol from cellulose technology.

Figure 1

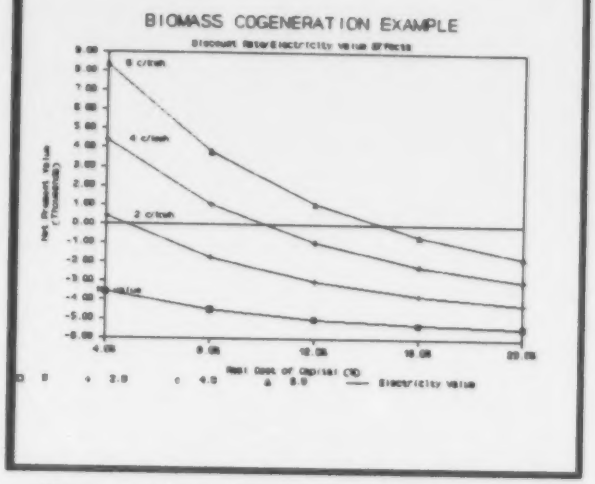
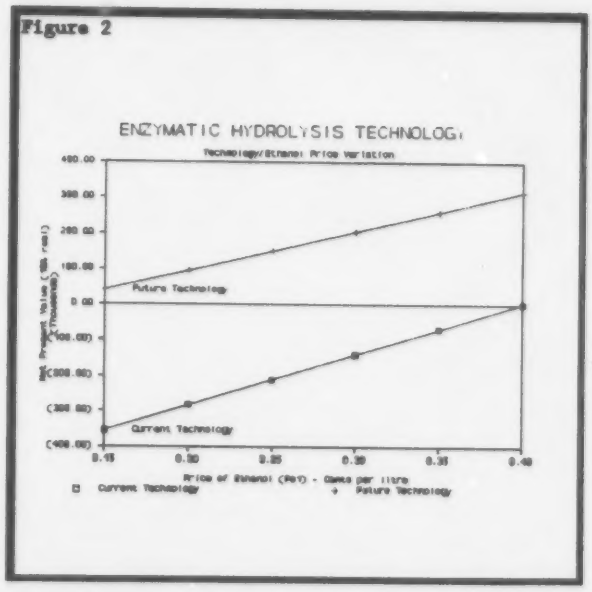


Figure 2 illustrates the positive impact on the economic attractiveness of this technology arising from expected improvements in technical process parameters such as enzyme productivity, enzyme loading and hydrolysis time.

Figure 2



3. Linkage with Technical Analysis Models

The convenient file save and retrieve feature of RETA 123 provides an effective means to link this model with the outputs from technical analysis models. The base data for these examples has been drawn from a recently developed model of Iogen's ethanol from cellulose process technology. This model has been designed to allow for the extraction of a structured output file which in turn serves as an input file for RETA 123.

The effect of changes in technical parameters on economic returns is illustrated in Figures 3 and 4. Figure 3 shows the economic effect on a base case plant scale of 1000 tonnes per day of introducing reasonable values for lignin, molasses and electricity coproducts. The results are most sensitive to lignin value, and least sensitive to the value of cogenerated electricity.

Figure 3

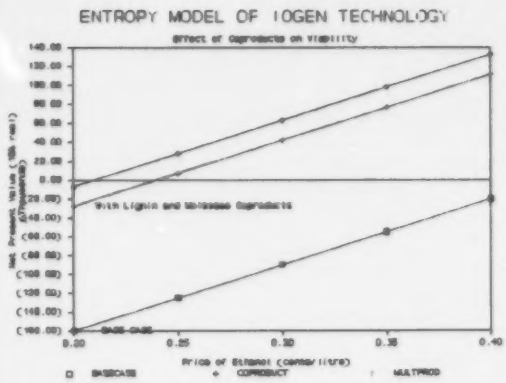
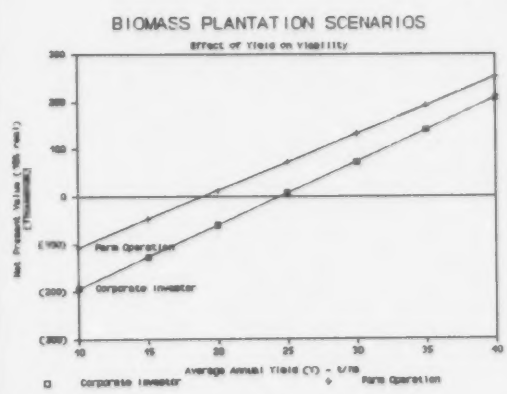


Figure 4 illustrates the effect of plant scale on economic returns, including coproduct values and assuming a range of ethanol selling prices.

Figure 4



4. TREE 123 - Investment Analysis for Biomass Plantations

The structured RETA 123 input format developed for WERET has been adapted to analyse the economic attractiveness of alternative scenarios for biomass plantation investments. TREE 123 was developed following a May 1988 workshop which examined the current status of research efforts and identified the relevant factors to be taken into account in examining the cost and performance of biomass plantation investments.

TREE 123 provides for the analysis of cyclic investment in production for biomass plantations. The model includes categories for initial costs, such as land and plantation stock, cyclic costs including tending, fertilization and maintenance, and end of cycle costs such as harvesting and transportation. Annual or cyclic yield factors can be specified or provided in a schedule, and data outputs and economic indicators are similar to those for RETA 123.

Figures 5 and 6 display output results from the TREE 123 model. Figure 5 illustrates the sensitivity in economic returns to changes in yield for two alternative approaches to biomass plantation investment. One is for a stand alone corporate investment, and the other is for a decision by an existing farming operation to reallocate land to fast growing tree production.

Figure 5

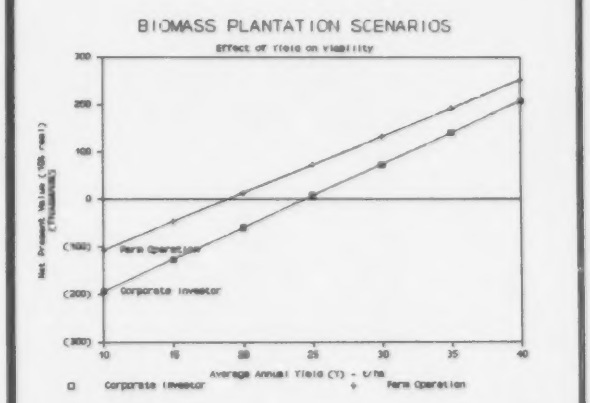
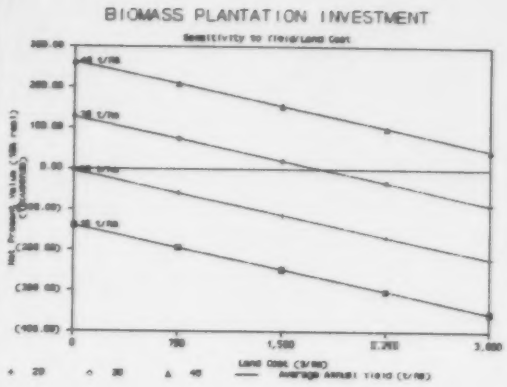


Figure 6 highlights the relationship between yield and land cost. For the example case presented here, the figure shows the potential returns from research on fast growing biomass feedstocks aimed at achieving higher yields. To the extent that land quality is directly related to cost, the results indicate that the use of higher cost land can be rationalized without a significant economic penalty.

Figure 6



DISCUSSION

RETA 123 offers a structured input format for analyzing the economic attractiveness and financial viability of renewable energy technology applications. The input data format is a condensed form of the technology cost factor formats (CPFF's) developed for the Workshop on the Economics of Renewable Energy Technologies (WERET). The model outputs are consistent with the calculations performed in each of the sector methodology analysis formats (SMAF's) developed for the Workshop.

The above examples illustrate the tremendous versatility of RETA 123 in conducting analyses of policy measures and comparative analyses of technology options. The expansion of the RETA 123 to link with a technology process model illustrates its usefulness for assisting in the strategic direction of R&D activity. The development of the TREE 123 model to analyse the economic viability of biomass plantation investments provides an added dimension to the use of such models and serves to emphasize this versatility.

The analysis results presented in this paper are only intended to illustrate the versatility of the models, although the data have been extracted from a number of recent technology feasibility studies. RETA 123 is now being used to assess the financial viability of specific bioenergy technology opportunities, as part of an integrated technology based planning process underway in the Energy Diversity Division of EMR. RETA 123 has also been used to analyse the Canadian examples developed for WERET, in a paper for the June 1989 Solar Energy Society of Canada (SESCI) conference.

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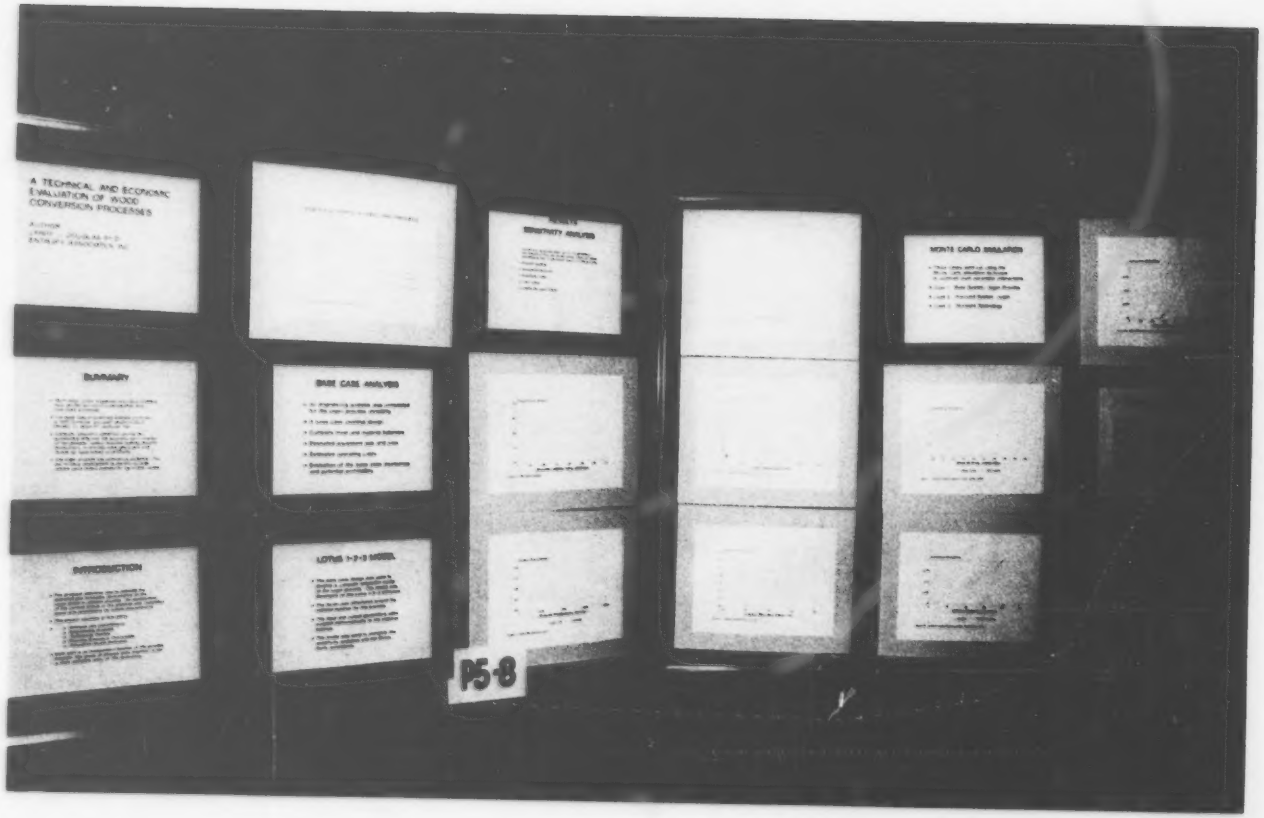
A TECHNICAL AND ECONOMIC EVALUATION OF WOOD CONVERSION PROCESSES
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BASE CASE ANALYSIS
LOTUS 1-2-3 MODEL
SENSITIVITY ANALYSIS
MONTE CARLO SIMULATION
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TECHNICAL AND ECONOMIC EVALUATION OF A WOOD-TO-ETHANOL PROCESS

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The Iogen enzymatic hydrolysis Wood-to-Ethanol process was the subject of a technical and economic analysis. The analysis consisted of four parts; first a review of the current status of the technology, second an engineering evaluation of the Iogen process and estimate of the current (or base case) economics; third a development of a computer model based on the engineering flowsheet; and fourth a complete set of sensitivity analysis and Monte Carlo simulations to assess the potential for future improvements to the process.

1. The technology review suggested that enzymatic processes have a greater potential to achieve commercial success than do the acid hydrolysis processes.
2. The base case engineering analysis of the Iogen process showed a potential for producing ethanol for about 52 cents/liter for a plant scale of 1000 tons of aspen wood per day and no co-product credits for lignin or C5 sugars other than as boiler fuels.
3. A computer model of the process was constructed on a Lotus 1-2-3 spreadsheet. The model connected the operating parameters of the process and calculated the heat and material balances, and capital and operating costs after any change to processing conditions.
4. The computer model was used to complete sensitivity analysis and Monte Carlo simulations. These data identified several parameters as key to the economic success of the process, these were: Enzyme loading, hydrolysis yield, enzyme productivity, lignin as a value added co-product and xylose as a value added co-product. Plant scale and pretreatment effectiveness were also important factors.

The result of this analysis shows that the Iogen process has commercial potential and that the key to early development is finding substantial value added markets for the lignin and xylose co-products.

Le procede Iogen, qui permet de transformer le bois en ethanol par hydrolyse enzymatique, a fait l'objet d'une analyse technique et economique. L'analyse comportait quatre volets: une etude de l'etat actuel de la technologie; une evaluation technique de procede Iogen et une evaluation des aspects economiques actuels (cas se base); la mise au point d'un modele informatise base sur le schema de fonctionnement; et la realisation d'une serie complete d'analyses de sensibilite et de simulations de Monte Carlo pour evaluer la possibilite d'ameliorer le procede.

1. L'etude technique a montre que les procedes enzymatiques sont plus susceptibles d'obtenir un succes commercial que les procedes d'hydrolyse acide.
2. L'etude des aspects economiques de procede Iogen a montre qu'il etait possible de produire de l'ethanol pour environ 52 cents/litre dans use usine pouvant traiter 1000 tonnes de bois de tremble par jour, sans credit de co-produit pour la lignine ni pour les sucres en C5 autrement que sous forme de combustibles servant a alimenter la chaudiere.
3. Un modele informatise du procede a ete elabore sur un tableur Lotus 1-2-3. Le modele permettait de relier les parametres de fonctionnement du procede et de calculer les bilans thermiques et les bilans massiques, ainsi que les couts en capital et les frais d'expolitation apres n'importe quel changement apporte aux conditions de traitement.
4. Le modele informatise a servi a realiser des analyses de sensibilite et des simulations de Monte Carlo. On a ainsi trouve plusierus parametres essentiels au secces economique du procede, a savoir l'apport d'enzyme, le rendement de l'hydrolyse, la productivite des enzymes, la lignine en tant que co-produit a valeur ajoutee et le zylose en tant que co-produit a valeur ajoutee. L'echelle de l'usine et l'efficacite du pre-traitement constituaient egalement des facteurs importants.

Les resultats de cette analyse montrent que le procede Iogen presente un potentiel commercial et que, pour assurer son developpement repide, il faut trouver des marches

importants pour la lignine et le zylose qui sont des sous-produits.

1. Introduction

The principal objective of this project was to complete a technical and economic evaluation of the Iogen enzymatic hydrolysis process for converting wood to ethanol. The evaluation includes an assessment of the current status of the technology and projections for future improvement.

The report consists of five parts:

- o The main body of the report with the analysis and conclusions.
- o Appendix A - the engineering analysis for the base case design.
- o Appendix B - a wood-to-ethanol technology review
- o Appendix C - A review of the process evaluation techniques used to complete this report.
- o Appendix D - A complete description of the Lotus 1-2-3 model develop to simulate the Iogen process

Attached to the end of the report in appendix E is a printout of the entire Lotus 1-2-3 computer model.

Each of the five individual parts of the report can be a free standing document, however, the group of reports work together to tell a more complete story. The technology review provides a general context to understand the process, the engineering section contains the detailed description of operation of the basic plant design, the process evaluation section describes the particular techniques used in the analysis and the rationale for their selection. The model description section describes how the model was construdted using the engineering data from the engineering section.

Finally, the main body of the report uses all the above data and information to generate the analysis and projections regarding the present and future economic potential for the process.

The project was completed as follows; first the technology review paper was completed and submitted to EMR, then the section on technology evaluation techniques was completed. The base case process engineering was done along with complete heat and material balances, capital cost estimates based on the Icarus computer-assisted costing program and an estimate for the base case economic performance.

The engineering design was the basis for construction of the Lotus 1-2-3 computer process simulation model. The computer model was used to run sensitivity analyses and Monte Carlo simulation. The results of these analyses provided the data for many of the conclusions and concerns discussed in the main body of the report.

2. Process Analyses

The Iogen process is a state-of-the-art enzymatic hydrolysis for converting wood to ethanol. The principal strengths of the process, that set it apart for competing processes, are the steam-explosion pretreatment and high rate for enzyme production (and thus low cost for enzyme). The structure of native wood is very complex and difficult to penetrate with chemical or microbiological agents.

Wood has three principal components; cellulose, hemicellulose, and lignin. the hyrolysis process converts the cellulose to glucose, which is subsequently fermented to ethanol. In the native wood, the cellulose is surrounded by hemicellulose and lignin in a matrix that is nearly impossible for enzymes to penetrate. Steam-explosion treatment opens the matrix and greatly increases the cellulolytic surface area available to enzymic attack. This pretreatment is the most cost-effective currently under development.

Sensitivity Analyses

A number of process parameters were evaluated using the technique of sensitivity analysis. The process economics were very sensitive to changes in enzyme loading and enzyme productivity. The results of these analyses are shown below.

Enzyme Loading:

The base case process used 25 I.U. of enzyme per gram of cellulose as the loading level. Figure 1 shows the relationship between enzyme loading and ethanol selling prices.

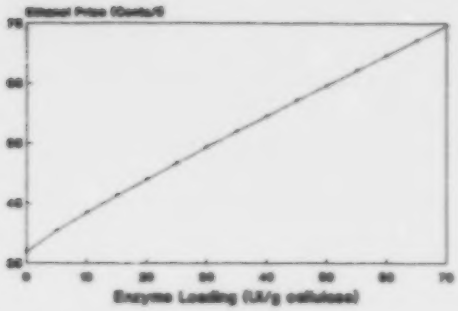

Figure 1. Enzyme Loading versus Ethanol Price

The loading amount was varied from 0 to 70 I.U. per gram of cellulose to generate the data plotted in figure 1. The ethanol price varied from 37 cents per liter to about 75 cents per liter. Enzyme loading is complex mixture of interaction among several process variables and often difficult to predict. Empirical data provide the only accurate measure of performance in this system. The Iogen data and the results of this computer analysis, both support and illustrates the economic sensitivity of this parameter.

Enzyme Productivity:

Lactose sugar from cheese whey is used as the carbon source for growing the cellulase enzyme complex in the Iogen process. The current productivity is in excess of 400 international units per liter per hour (I.U.). The estimated ethanol selling price is about 50 cents per liter. The importance of enzyme productivity is seen in the figure 1.

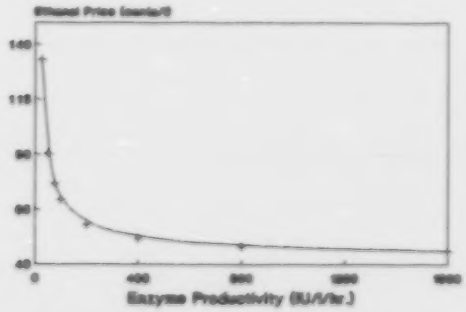

Figure 2. Enzyme Productivity versus Ethanol Price

If cellulose is used as the carbon source for enzyme production, the highest rate of productivity achieved to date is in the range of 50 to 100 I.U. The consequence of this lower productivity is an increase in the ethanol selling price to $1 to $1.50 per liter. This curve illustrates the importance of productivity to the economics of the process; it is important to note that additional increases in productivity can be expected through further research.

Monte Carlo Simulation

The purpose of the Monte Carlo simulation was to assess the potential for improvement to the economic performance of the Iogen process. The simulation process allows multivariable analyses and an assessment of the impact of uncertainty on achieving the target goals.

A Monte Carlo simulation was run to approximate an improved case for the process. Two simulations were run, with and without lignin co-product credit. The figure below shows the results of this simulation.

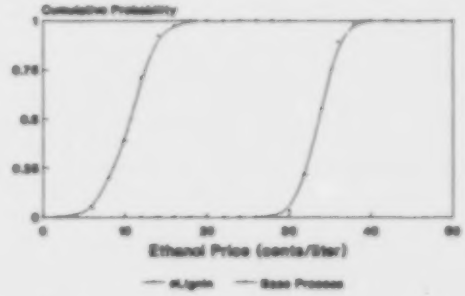

Figure 3. Monte Carlo Simulation: Improved Case

The inputs to the simulation were selected for their potential impact on the process economics and a reasonable expectation for attainability through research and engineering improvements to the process. The resultant simulation indicated that the ethanol price would be reduced to about 34 cent per liter for the base process and to about 12 cents per liter if co-procuct credit for lignin is included.

3. Discussion

The Iogen process is a state-of-the -art process for the enzymatic conversion of the cellulosic fraction of woody feedstocks to ethanol, that features co-production of chemicals and animal feed from the lignin and xylose fractions. The co-products add significant revenues to the plant and, therefore, enhance the economic potential of the process. In fact, without these

co-product credits it is doubtful if this, or any wood-to-ethanol process, could compete in the commercial environment.

The Iogen process scaled up to 1000 tonnes per day of wood input is estimated to produce ethanol that would sell for about 50 cents per liter without co-product credits. With co-product credits for the lignin and molasses the ethanol price would drop to between 25 and 30 cents per liter for the base case process.

Projected process improvements and higher valued markets for the lignin suggest the ethanol price could be reduced to 15 to 20 cents per liter and perhaps even lower.

4. Recommendations

The three modifications to the Iogen process suggested below are offered as potential methods to improve an already highly optimized process. These are outside the natural evolution of process improvements that are on going at Iogen.

1. SSF versus SHF. End-product inhibition causes the enzymatic hydrolysis process to slow down after the accumulation of sugars in the hydrolysis reactor. The simultaneous saccharification and sermentation (SSF) processing approach removes sugar from solution as it is made thus avoiding the problem of sugar accumulation. This reduced sugar accumulation also reduces the enzyme loading requirements for the process to the range of 10 I.U. per gram of cellulose. This translates to a reduction in the ethanol selling price from the base case value of 52 cents per liter to about 40 cents per liter.

2. Xylose to Ethanol. Conversion of the xylose sugars to ethanol would benefit the economics of the process by reducing the ethanol price from the base case value of 51 cents per liter to about 33 cents per liter. At present, the process to effect this conversion is a research issue, however, significant progress has been made to this end over the past two years. It is expected that a viable system for xylose fermentation will be available in the next two years and this option should be added to the Iogen process design.

3. Extracting the lignin prior to hydrolysis has beneficial effects on the process economics. Removal of lignin reduces the size and capital cost of some of the down stream equipment. Lignin removed via alcohol or base is of higher quality than fermentation lignin typical of the product from the Iogen process. By 'higher quality' I mean free of major contaminants, such as, unhydrolyzed carbohydrates.

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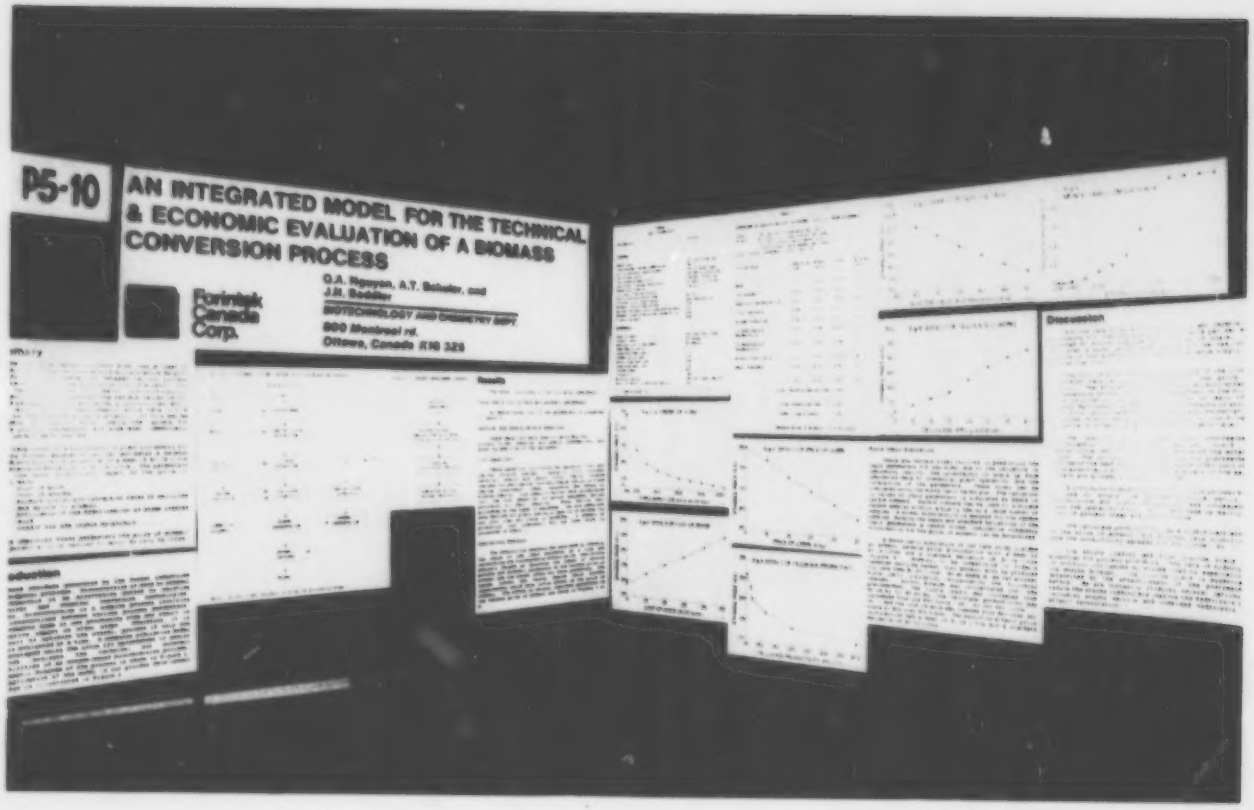
P5-10
AN INTEGRATED MODEL FOR THE TECHNICAL & ECONOMIC EVALUATION OF A BIOMASS CONVERSION PROCESS
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Discussion

AN INTEGRATED MODEL FOR THE TECHNICAL AND ECONOMIC EVALUATION OF A BIOMASS CONVERSION PROCESS

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Wood residues generated from lumber and composite-product mills pose disposal problems. Bioconversion of wood to ethanol and chemicals is an alternative method to existing mechanical and chemical conversion technologies. However, bioconversion is a complex process with many interactions between various process parameters. Improvements made in one processing step may result in negative impact on other steps. Therefore, it is difficult to optimize the overall process if each step is evaluated independently.

A process simulation model was constructed, using Lotus 123 spreadsheet, to evaluate the technical and economic feasibility of a lignocellulosic-to-ethanol bioconversion process, and to optimize the process parameters. The major components of the process are: steam pretreatment, fractionation, lignin recovery, enzyme production, enzymatic hydrolysis, ethanol fermentation of glucose, ethanol fermentation of xylose, ethanol distillation, and waste treatment.

The model consists of an input table for process and economic parameters, a set of material and energy balance equations, a set of cost equations, an output table showing the revenue price of ethanol and the breakdown of operating and capital costs for each processing component, and a Monte Carlo risk simulation. Operating costs include costs of raw materials, chemicals, utilities and labour. Fixed capital costs are calculated using the capital-recovery-factor method, which incorporates the rate of return on investment, interest charges, depreciation costs, taxes and insurance premiums. A case study of a 500 OD tonne aspen wood/day plant estimates a revenue price of ethanol at $0.78/litre. The parameters having the most significant impact on the price of ethanol are: the cost of wood, the cost of enzyme, the product yields and conversion rates in cellulose hydrolysis and ethanol fermentation of xylose, the efficiency of fractionation of steam treated wood, and the credit for lignin by-product. By improving these parameters the price of ethanol can potentially be reduced to about $0.25-0.30/litre.

The model has been an effective tool in helping us achieve a better focus for our bioconversion research and development program.

Les résidus de bois rejetés par les usines de sciage et les usines de fabrication de produits composites constituent un problème sur le plan de l'élimination. La bioconversion du bois en éthanol et en produits chimiques permet de remplacer les techniques mécaniques et chimiques actuelles de conversion. Toutefois, la bioconversion est un procédé complexe au cours duquel on observe de nombreuses interactions entre les divers paramètres qui la régissent. Les améliorations apportées à une étape du procédé peuvent se traduire par un impact négatif sur les autres étapes. On peut donc difficilement optimiser globalement le procédé en évaluant individuellement chaque étape.

On a élaboré, à l'aide d'un tableur Lotus 123, un modèle de simulation permettant d'évaluer la rentabilité technique et économique d'un procédé de bioconversion des matières ligno-cellulosiques en éthanol, et d'optimiser les paramètres qui le régissent. Voici les principales étapes du procédé: pré-traitement à la vapeur, fractionnement, récupération de la lignine, production d'enzymes, hydrolyse enzymatique, fermentation du glucose en éthanol, fermentation du xylose en éthanol, distillation de l'éthanol et traitement des résidus.

Le modèle comprend une table d'entrée pour les paramètres régissant le procédé et pour les paramètres économiques, un ensemble d'équations représentant le bilan massique et le bilan énergétique, un ensemble d'équations représentant les coûts, une table de sortie présentant le prix de l'éthanol et la ventilation des coûts d'exploitation et des coûts en capital pour chaque constituant du procédé, ainsi qu'une simulation de Monte Carlo permettant d'évaluer les risques. Les coûts d'exploitation comprennent le coût des matières premières, le coût des produits chimiques, le coût des services publics et le coût de la main-d'oeuvre. On calcule les coûts fixes en capital à l'aide de la méthode du facteur de recouvrement du capital, qui

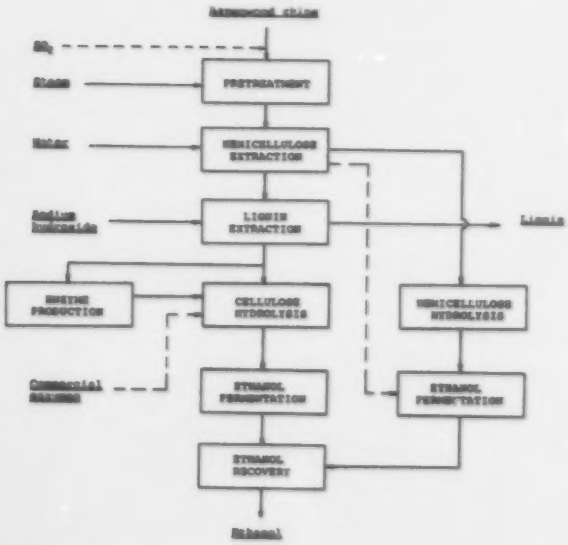
tient compte du taux de rendement sur les investissements, des frais d'intérêts, de l'amortissement, des taxes et des primes d'assurance. Une étude de cas portant sur une usine pouvant traiter 500 tonnes de bois de tremble (séché à l'étuve) par jour a permis d'estimer le prix de l'éthanol à 0,78 $/litre. Voici les paramètres qui influaient le plus sur le prix de l'éthanol: le coût du bois, le coût de l'enzyme, les rendements en produit et les taux de conversion pendant l'hydrolyse de la cellulose et la fermentation du xylose en éthanol, l'efficacité du fractionnement du bois traité à la vapeur et les crédits pour la lignine qui constitue un sous-produit. Il serait possible de réduire le prix de l'éthanol à environ 0,25-0,30 $/litre en améliorant les paramètres.

Ce modèle a été un outil utile qui nous a permis d'examiner dans une meilleure perspective notre programme de recherche et de développement sur la bioconversion.

INTRODUCTION

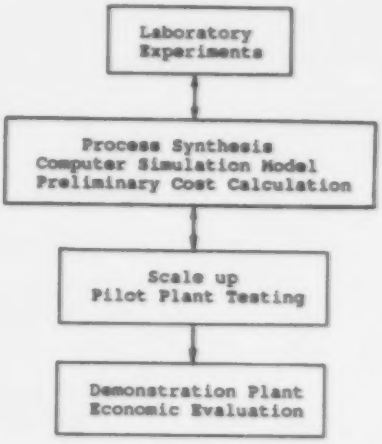
Wood residues generated by the forest industries pose disposal problems. Bioconversion of wood to ethanol and chemicals is an alternative method to existing mechanical and chemical conversion technologies. However, bioconversion is a complex process involving many interactions between various process parameters. Improvements made in one processing step may result in a negative impact on other steps. Therefore, it is difficult to optimize the overall process if only one step is evaluated at a time. A computer simulation model was developed using the Lotus 123 spreadsheet to assist Forintek evaluating the technical and economic feasibilities of an enzyme-based bioconversion process. A schematic diagram of the process is shown in Figure 1. The application of the model in our process development strategy is illustrated in Figure 2.

Figure 1 SCHEMATIC FLOW DIAGRAM OF A BIOCONVERSION PROCESS



Note: Broken lines represent alternative processing steps

Figure 2 PROCESS DEVELOPMENT STRATEGY



RESULTS

The model consisted of the following components:

Input table for process and economic parameters

An abbreviated list of the parameters is presented in Table 1.

Material and energy balance equations

These equations were used to calculate the process flows, material and energy consumptions, and quantity and size of the equipment.

Cost equations

These equations calculated the operating costs and capital related charges. Operating costs included material, energy and labour costs. Capital related charges included capital recovery charge[1] (return on fixed capital investment), taxes, insurance, and return on working capital. Cost-capacity factors[2] were incorporated into the cost equations to adjust equipment prices according to their capacity. These factors vary according to the types of equipment. The cost equations were derived for plants having a capacity of between 100 and 1000 oven dry tonne

of wood/day. A summary of production cost components for our case study is presented in Table 2.

TABLE 1
Input Parameters*

Parameters	Values
PROCESS	
Wood input	500 dry tonne/day
Pretreatment-steam temperature	240 °C
Solid recovery (pretreatment)	92% of wood input
Cellulase yield	180 FPU/g cellulose
Cellulase productivity	104 FPU $litre^{-1}$ hr^{-1}
Cellulase loading (hydrolysis)	18 FPU/g cellulose
Substrate loading (in cellulose hydrolysis)	10% w/v
Cellulose hydrolysis time	48 hr
Glucose yield (hydrolysis)	85% theoretical
Ethanol yield from glucose	95%
Xylose recovery yield from pretreatment	55%
Ethanol yield from xylose fermentation	90%
Lignin recovery	85%
ECONOMICS	
Cost of wood	$60/oven dry tonne
Lignin credit	$0.08/kg
Service life of equipment	20 years
Debt/Equity ratio	0.3
Long-term debt ratio	0.3
Common stock cost	15%
Short-term debt cost	15%
Long-term debt cost	11%
Income taxes	45%
Inflation	6%
Working capital	8% (of fixed capital)
Rate of return on working capital	25%

* : Abbreviated list

TABLE 2
BREAKDOWN OF PRODUCTION COST OF ETHANOL ($/litre) FROM ASPENWOOD

Input = 500 oven dry tonnes wood per day
Output= 49.5 million litres ethanol per year (or 300 litres/tonne of wood) plus 31,500 tonnes lignin powder per year
Total capital investment = $ 81.5 million

Process Area	Operating Cost	Fixed Capital	Total	% Total Cost
Wood	0.20	0.00	0.20	25
Pretreatment	0.06	0.01	0.07	9
Hemicellulose Extraction	0.03	0.02	0.05	6
Lignin Recovery	0.09	0.02	0.11	13.5
Enzyme Production	0.06	0.05	0.11	13.5
C6 Hydrolysis & Fermentation	0.05	0.04	0.09	11
C5 Hydrolysis & Fermentation	0.01	0.03	0.04	5
Ethanol Distillation	0.11	0.01	0.12	14
Waste Treatment	0.00	0.02	0.02	2
	0.61	0.20	0.81	100
Plus: Working Capital Cost			0.02	
Total Production Cost			0.83	
Less: Lignin Credit			0.05	
Revenue Price of Ethanol = $ 0.78/litre				

Sensitivity analysis

The sensitivity analysis was performed by changing the value of one input parameter at a time and calculating the corresponding ethanol price. Sensitivity analysis helped us determine the impact of various process and economic parameters on the revenue price of ethanol and the target levels for these parameters. The target levels are values beyond which further improvements would have little effect on the price of ethanol. The effect of several important parameters on the revenue price of ethanol are shown in Figures 3 to 8.

Monte Carlo simulation

There are certain risks involved in predicting the input parameters for the model due to the variation in laboratory results, the uncertainty in scale up from laboratory data to commercial plant operation, and the interaction of the parameters. These risks can be simulated using the Monte Carlo technique[3,4]. The variation in values of input parameters is simulated by means of random numbers. Random numbers can be used to simulate random samples without actually taking a large number of samples. A normal distribution is assumed for the random samples. Knowing the means and standard deviations of the input parameters a random normal cumulative-frequency distribution for the price of ethanol can be determined.

A Monte Carlo simulation of our case study yielded an ethanol revenue price distribution with a mean of $0.78/litre and a standard deviation of $0.06/litre (Figure 9). However, to be competitive in today's Canadian gasoline market, fuel ethanol must be produced for less than $0.25/litre. As an example, we ran another Monte Carlo simulation incorporating the following changes. Sulfur dioxide was incorporated into the pretreatment, the lignin credit was increased from $0.08/kg to $0.60/kg, the cellulase productivity was increased from 104 FPU $litre^{-1}$ hr^{-1} to 150 FPU $litre^{-1}$ hr^{-1}, and the cost of wood was lowered from $60/oven dry tonne to $25/oven dry tonne. The resulting ethanol price distribution had a mean of $0.26/litre and a standard deviation of $0.03/litre.

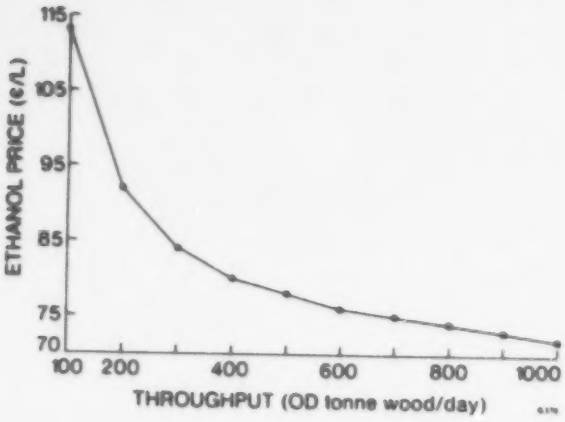


Figure 3 Economy of Scale

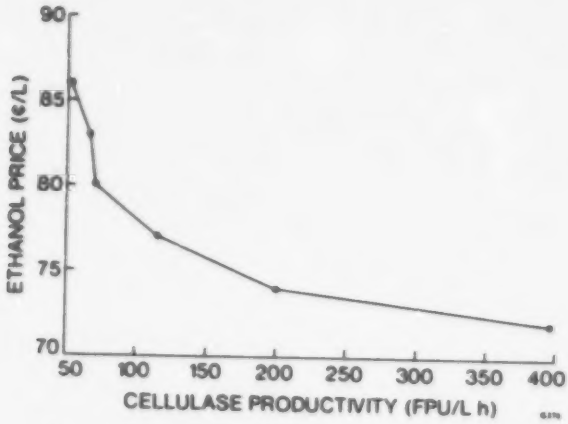


Figure 6 Effect of Cellulase Productivity

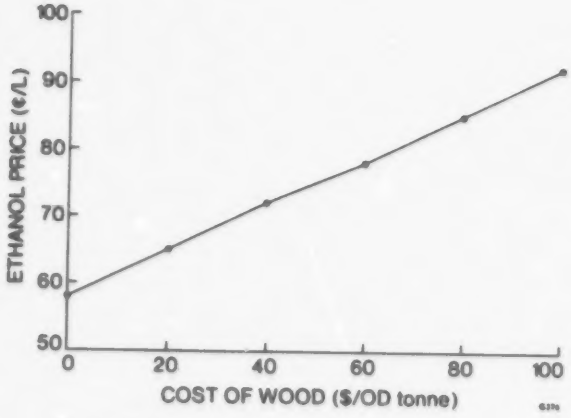


Figure 4 Effect of Cost of Wood

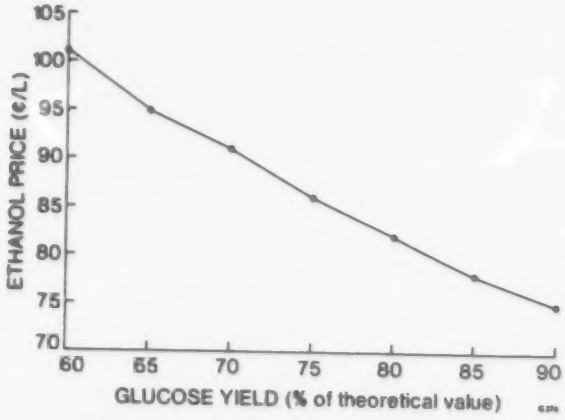


Figure 7 Effect of Glucose Yield

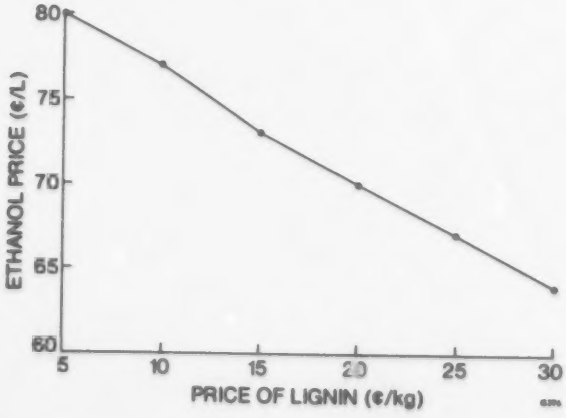


Figure 5 Effect of Price of Lignin

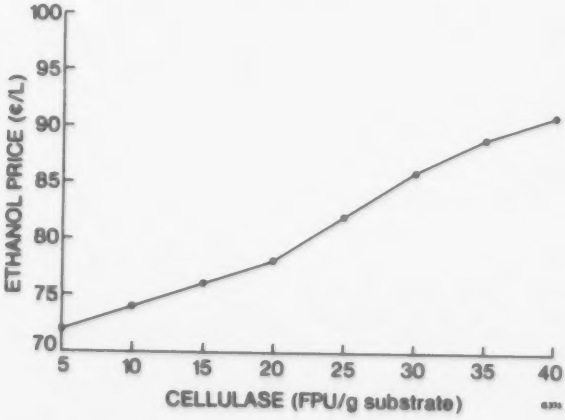


Figure 8 Effect of Cellulase Loading

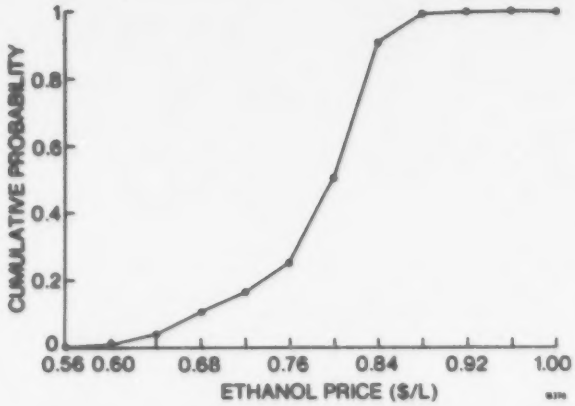


Figure 9 Monte Carlo Simulation

DISCUSSION

For our case study a bioconversion plant capable of processing 500 oven dry tonne of aspen wood per day was selected to ensure reasonable economies of scale. We feel that a much larger plant would not be realistic because of the difficulty in securing a large supply of wood at low cost.

The cost of wood and the selling price of the lignin by-product have a profound effect on the price of ethanol. The economic viability of a wood-to-ethanol bioconversion process is strongly dependent on the high-value utilization of lignin as it is unlikely that process improvements alone -- e.g. improvements in enzyme production, cellulose hydrolysis and ethanol fermentation of xylose, fractionation efficiency, etc. -- could lower the price of ethanol to a commercially viable level.

The use of SO_2 in the steam pretreatment significantly increased the recovery yield of hemicellulose[5], which consequently increased the ethanol output. The inclusion of the SO_2 in the pretreatment eliminated the need for the hemicellulose hydrolysis step since essentially all the fermentable sugars in the water extract are already in monomeric form.

A continuous counter-current extraction process must be used to attain low solvent-to-solid ratios in hemicellulose and lignin extractions and consequently lower the operating costs, which are made up mainly of costs of process steam and caustic soda.

The cellulase productivity has a significant effect on the price of ethanol, but becomes less significant once the productivity exceeds 200 FPU $litre^{-1}$ hr^{-1}.

Low enzyme loading and high glucose yield are essential for process economics. The rate of hydrolysis is strongly influenced by enzyme loading especially at low enzyme dosages. The glucose yield is essentially determined by the effectiveness of the pretreatment method. We are currently studying several options to reduce the enzyme loading and improve the hydrolysis rate including enzyme recycle and combined hydrolysis and ethanol fermentation.

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WORKSHOPS

ATELIERS

BIOCONVERSION WORKSHOP

R.D. Hayes

Energy, Mines and Resources Canada
Ottawa, Ontario

INTRODUCTION

This workshop was held following the 7th Bioenergy R&D Seminar, at the Skyline Hotel, Ottawa, April 23-26, 1989.

Key theme of the workshop was to discuss ideas for maintaining the critical mass of Bioenergy R&D work in the face of major cut backs in Federal budget support.

Aspects that were discussed involved:

1. Increased participation by the industry in R,D&D.

2. Enhanced efforts by the Bioenergy Community to educate the public on bioenergy, and the environmental benefits of its widespread use.

Industrial Participation

The new policy requires an increased industrial participation, at least up to 25 percent of total project value. Because the industry objectives and needs are often different than the R&D needs, specially at the first steps of the innovation process, these levels may be difficult to achieve. It is desirable to differentiate between the types of research when specifying industry participation levels, and presentations should be made to the appropriate agencies in this regard.

Some of the participants felt that perhaps the reason for these somewhat unreasonable industrial participation expectations is the lack of political clout of the Bioenergy Community. With environment being a key issue of the nineties, the community should highlight the CO2 reduction benefits of bioenergy.

At least one participant indicated that industry was very much willing to invest money in bioenergy R&D when it faced a problem. Perhaps, bioenergy research should be designed to solve problems in the pulp and paper, agriculture and environmental industries.

A key problem with industrial involvement in Bioenergy R&D is the absence of a bioenergy industry in Canada. Although Bioenergy R&D effects a number of industries, it does not have a direct industry champion. Otherwise perhaps industry participation would not be a big problem.

Public Education

This subject lead to a lively discussion. Important suggestions that require some thought include:

1. Increased biomass use will lead to reduced CO2 level. The community must connect the two issues, and present it to the public actively, to foster the image that bioenergy will solve greenhouse effect problem.

2. Point out to environmental policy makers that bioenergy can play a key role in achieving the CO2 reductions well beyond the year 2000 target.

3. Use Biojoule as a key vehicle to foster the environmental friendly image of bioenergy. Community members can produce position papers, that can be presented at various forums and media under the BEI banner.

4. It should be pointed out that through the use of bioenergy, the country can achieve the desired CO2 level reductions <u>without</u> accepting a reduction in our standard of living.

5. It is important that we speak in people's language when educating them on the greenhouse issues. Don't tell the farmer about the country heating up by 2-3[C by year 2020. Talk about not having enough water for their cattle. Similarly, sell the harvesting of the straw or chaff to farmers by telling them how much additional money they can make.

6. We should attempt to train agricultural professionals in bioenergy.

7. The Community should get out and go to other conferences to present bioenergy/R&D.

8. The Community has two main customers; the public-at-large, and decision makers in Ottawa. Educational and promotional strategies should target both groups.

9. Thinking within EM&R has changed substantially over the last few years because of the efforts of Renewable Energy Branch personnel. Education outside the Department is also the Community's responsibility.

10. A key problem in the bioenergy area is that there is no "ready-made" econometric data available on bioenergy. Should an effort be made to generate such data? Somebody should be writing an article on the subject that can be published in Biojoule and can be used to influence future econometric studies.

R&D WORKSHOP MINUTES

Thermochemical Conversion Workshop
April 26, 1989

WORKSHOP DISCUSSIONS AND CONCLUSIONS

1. Centralized Analysis at BC Research

Jim KcKinley reviewed the historical development of the Centralized Analysis Service at B.C. Research Corp. (BCR). Analyses are currently being carried out in cooperation with the following: U. de Sherbrooke, U. of Toronto, U. Laval, Waterloo U., Ensyn Engineering and Solar Energy Research Institute (SERI). Two types of projects are included in their mandate. The first is a simple service function in which a participating laboratory sends the sample to be analysed by a well known method and receives the results just as they might have done from a commercial laboratory. The second type is more development oriented, in which the BCR personnel are directly involved in the participating laboratories project, in order to develop the solution to a specific problem. Naturally, it is the second type of project which is more appealing to the staff at BCR; never the less, the staff and equipment allotted to the project have been upgraded so that in the future, researchers will receive their results much more rapidly than has been possible in the past.

The standard analysis services, provided for under the contract are:

- elemental analysis;
- water content
- vapour pressure osmometry;
- TGA;
- g.c. analysis;
- g.c./mass spec.;
- proton and C-13 NMR;
- simulated distillations.

The workshop discussed the activities of BCR and gave the following principal conclusions and recommendations:

- The service was endorsed (unreservedly) by the participants. Researchers with similar in-house analytical capabilities stressed that the service was valuable for verification of their own methods.

  Researchers without an in-house analytical capability were very dependent on BCR for understanding the science of their process and to accomplish optimization of process development.

- It was clearly reiterated that there is a provision in the general centralized analysis service contract for specific "mini-proposals" from researchers. If a specialized type of analysis is required or if unique services must be performed by BCR staff, a proposal can be prepared jointly and submitted to EMR and the Scientific Authority (RPO) for approval as a Task under the existing contract. With the current contract remaining in effect for about 18 months, there is time for new tasks to be initiated.

- Several researchers were interested in physical characterization and analysis of solid state samples, including biomass feedstocks (elemental, TGA, moisture, particle size) and catalyst (pore size, surface area, etc.). It was concluded that these might fall under the mandate of special projects within the general services contract. Solvent extraction (and other extraction techniques) of compounds or classes of compounds from the liquid product "syrop" was also an area which could be covered by special projects.

- There was some concern over the change in sample properties (i.e., "shelf life") during storage, transport, etc., prior to analyses. It was suggested that a RECOMMENDED protocol for handling, storing and shipping samples be developed by BCR and the community.

2. The IEA CHO and Water Analysis Round-Robin:

A question on the reliability of "oxygen by difference" led Jim McKinley to review the International Energy Agency (IEA) round-robin evaluation of analytical methods. The first of these under the thermochemical task has been completed on the ultimate analysis and moisture analysis of two biomass liquefaction oils prepared by Waterloo U. and LBL. A paper is in preparation but the preliminary results show that carbon, hydrogen and oxygen (CHO) analyses (O by difference) were reasonably consistent. The values for the water analysis are less so. At first glance the direct oxygen determinations are

much less consistent and are not as accurate as those by determined difference.

Several other tests were proposed for evaluation: e.g. simulated distillation, aromatic and aliphatic hydrogen contents. Unlike the ultimate and water analyses which are the basis of interlaboratory comparisons of H/C ratios and the calculated energy content of a given oil, these other proposals are much more research oriented and will require some greater level of consequence to be adopted by the community as a future round-robin. When the results of the first round-robin are ready, they will be disseminated widely for comment and suggestions as to further tests at that time.

3. The IEA Voluntary Standards Activity

Tom Milne from SERI, the organisor of the overall IEA voluntary standards activity, reviewed the three principal objectives of the program:

(1) Interlaboratory comparisons of "standard" analytical methods in biochemical and thermochemical conversion, and in biomass feedstock analysis. This activity is known colloquially as Round-Robins.

(2) The identification of standard reference materials from both wood and herbaceous biomass materials.

(3) The preparation of a Sourcebook of Methods of Analysis for Biomass and products of processes producing fuels and chemicals.

Three round-robins were recommended as part of the inter-laboratory comparisons task: enzyme studies (enzyme hydrolysis of a reference feedstock and protein determination); analyses of pyrolysis and liquefaction oils (moisture and ultimate analysis); and the analysis of specified biomass feedstocks. The results of the enzyme hydrolysis/protein determination round-robin have been compiled, are being reviewed, and will soon be published in the scientific literature. The progress on the pyrolysis/liquefaction oil round robin is described above. The biomass feedstocks analysis round-robin results will be released at a later date.

With respect to the reference biomass materials, it was stated that it would be unlikely that these will be expanded beyond the existing four "standards", which are now available from the old National Bureau of Standards (NBS) now NIST - The National Institute of Standards and Technology - Standard Materials Collection. The existing standards include a hardwood (Populus), a softwood (Pinus) and two agricultural residues (wheat straw and bagasse).

Even though there is a keen current interest in "lignin", the identification of a lignin standard was considered to be minefield since all methods of isolation alter the structure. The "unofficial" cellulose standard is Avicel for the thermochemists and Sigma for the biotechnologists. Both are in widespread use.

The Sourcebook has been completed and is out for review but has not yet been published. Tom Milne pointed out that it is truly a source book and is not an analytical handbook.

4. Feedstocks

The Canadian community was in the forefront in the adoption of a standard poplar feedstock for intergroup comparisons of thermochemical and biological conversion processes. In view of the extensive data bank already developed for this material, it was generally concluded that this feedstock continue to be used when comparisons of processes (inter) or of operating conditions (intra) are desired. A list of other recommended biomass feedstocks was proposed:

- willows
- juvenile biomass
- MSW
- selected residue streams
- segregated waste streams

The willows were suggested because of the current interest within other international biomass research program (especially Europe), and also their tremendous potential for rapid growth which has been demonstrated by production/silvicultural studies of the IEA task 5. The expansion into municipal solid waste (MSW), refuse derived fuel (RDF) and other waste streams (including industrial waste, scrap tires and waste fats and oils, and "as is" forest industry residues, etc.) should be a high priority for Canadian bioenergy processes since they can be driven by the increasing public environmental awareness and concern. Thus, energy becomes a valuable byproduct of what is primarily a waste disposal/environmental process. This type of application has good potential for export to Europe and the U.S.A.

Some participants suggested that the bioenergy community expand its process applications by going for applications on known industrial waste material streams (and more specifically polluting streams) of materials in order to apply bioenergy solutions already developed under the Bioenergy Development Program (BDP). Among these solid/liquid waste management problems, several options were identified including: scrap tires, RDF, mixed forest residues and lignin derived waste streams. It was evident that with several advanced thermochemical processes under development in Canada, there is a wish to take a global view of opportunities and export technology packages.

5. Oxy-Chemicals

Biomass materials are, by nature, most suited to the production of oxy-chemicals, even though from the energy perspective most of the upgrading processes have focussed on oxygen and carbon rejection to produce hydrocarbons and petroleum industry chemical substitutes. There was a

general consensus that in view of the presence of oxygen in the feedstock, perhaps a better strategy would be to look at new and existing markets for oxy-chemicals derived from biomass rather than hydrocarbons from biomass. Surfactants, new plastics, adhesives and polymers, levoglucosan derivatives, etc., were all listed as candidates. It is likely that if this approach is to be successful, the feedstock should be fractionated into its principal components (cellulose, lignin hemicellulose) prior to conversion to enhance product selectivity. Thus a refinery approach to biomass conversion has to be adopted which parallels the petroleum industry model, though yielding a different slate of products. Catalytic cracking using a variety of catalysts, was also suggested as a promising area of investigation when coupled with prior biomass fractionation.

6. Gasification

It was the general opinion of the workshop that very little fundamental or applied R&D is required for carrying air or oxygen gasification into the market place. An exception is hot gas cleanup (for tar and particulate removal). Gasification still has a role to play in biomass conversion, especially in kiln and dryer applications and boiler retrofit. A number of Northern European countries have had some major recent commercial successes in these applications of gasification. In Canada, a successful demonstration project will be required in order to overcome the negative track record perceived for this technology by the forest products industry (even when favourable economics are apparent).

The Biosyn project to scale up fluidized bed high pressure air and oxygen gasification was technically successful as far as it went, unfortunately its focus was on the methanol and liquid fuels market for which the economics have become increasingly poor. The Centre Quebecois de Valorisation de la Biomasse (CQVB) is the licencor of this technology following the termination of the project.

7. Other Topics

- A need was expressed to look at separation of components in the "oils" produced by liquefaction and pyrolysis. This could likely be handled in part by "mini-proposals" to BCR via the centralized analysis contract.

- Many researchers were confused by the federal government's technology transfer policy with respect to ownership, licensing, Canadian Patents and Development Ltd.'s (CPDL) role, etc., especially when cost-sharing is involved. These issues should be resolved when the contract is initiated rather than when it is in progress or at completion.

- Promising Canadian technologies often do not proceed beyond the "PDU" (process development unit) level of development. The question was raised as to what private and public mechanisms are in place to carry on the development to commercialization. What role can the process developers expect to play as development proceeds? What must they give up in order to raise capital, etc.?

8. Conclusions

The workshop re-emphasized the general observation that could be made about the 1989 Bioenergy R&D conference; that the development programs have been successful in bringing to the PDU stage a number of thermochemical technologies. The maturity of the programs extends to the scientific support such as the quality of the BCR analytical effort in support of the pyrolysis programs. While much of the work was initiated in the late 70's and early 80's in support of energy self sufficiency goals, these have now changed. In the new era how best can the sunk investment, and accumulated expertise be utilized? The workshop identified biomass fractionation and the production of added value oxy-chemicals from the fractions as a major avenue to pursue. Equally, technology transfer of processes from the biomass substrates to other waste and pollution streams could be seen as part of an overall strategy towards sustainable industries based on both renewable and non-renewable resources in a world that is becoming increasingly concerned about the environment. There was no doubt in the minds of the workshop participants that the energy question would return in the medium to long term future, not in the energy crisis context of the 70's but as part of sustainable development. This will call for a much more integrated solution to the energy, development and environment equation than were proposed this time. This along with the increasing globalization of trade and development makes this area one that should be maintained and even promoted over the next 5 years. Many institutional barriers to this could be seen and one of them, the technology transfer question, has to be quickly resolved.

WORKSHOP ON DIRECT COMBUSTION AND MATERIALS HANDLING

April 26, 1989

CHAIRMAN: BILL REYNEN, TECHNOLOGY BRANCH, ENERGY, MINES AND RESOURCES
SECRETARY: DON HUFFMAN, ENSYN ENGINEERING AND ASSOCIATES INC.

Following a brief introduction by the workshop Chairman, Bill Reynen, several participants provided short presentations on their recent research, development and commercialization activities.

N. Bundalli; B.C. Research

A short outline of recent work by B.C. Research was presented covering the mass-flow bin and non-consolidating feeder, the dense phase pneumatic transfer system, the rock separator system and the modified screw press dewatering system. It was noted that there is a need for technology transfer and marketing assistance to commercialize those systems for which the R&D has been successfully completed. It is very difficult to get research funds from industries who are primarily interested only in guaranteed results. Difficulties are also experienced when research must move into a co-operative venture within industry. Work must be tied into the mill's production schedule which tends to delay the progress; however, when successful, the technology (or system) receives quick industrial acceptance.

W. Edwards; B.H. Levelton and Associates

Work at B.H. Levelton and Associates on the laboratory and pilot-scale development of a water resistant DBF and on fundamental studies of hog fuel mechanical dewatering were reviewed. It was noted that it is very difficult to get mills to provide financial support even for optimizing the performance of existing equipment when research studies have already established that economic benefits can be realized.

P. Zundel; Wood Energy Applications

Studies by the University of Moncton have illustrated potential benefits from full tree harvesting/hauling and centralized tree processing. Three forest industry companies have been identified as potential participants in a future commercial operation, but a mechanism is required to reduce the

financial risk associated with a prototype since industry is reluctant to put up the capital for an unproven system. The results of bioenergy technology projects must be transferred directly to the industry, possibly by cooperation with associations such as COFI and CPPA.

D. Hirschhorn; Wardrop Engineering

Operation of the Wardrop Engineering 1-3 kg/h PDU for the superheated steam drying of hog fuel and sludge was reviewed.

A major segment of the workshop was devoted to a discussion of the current bioenergy activities in the U.S. as presented by a representative of the National Wood Energy Association. Major points covered were as follows:

* The U.S. DOE does no direct R&D in combustion or solid biofuel preparation and handling but does provide seed money as an incentive to include a specific technology within a regional biomass program project that is going ahead anyway. Information developed by this demonstration is then within the public domain and is transferred to other applications.

* In contrast to Canada (where there is no bioenergy industry and consequently no Canadian industry association) there is a growing bioenergy industry in the U.S. As a result of PURPA, limited potential for coal fired utilities and growing costs for landfill (new legislation requiring leachate and air-emission controls can raise tipping fees to over $60/t), the development of biomass fired utility generating plants (over 5100 MW) has created a significant biomass utilization industry that is very concerned about boiler efficiency.

* Efforts are currently underway to obtain legislation for a joint venture project to develop and construct a SOA biomass fired co-generation facility that would establish a new baseline on technology and emissions from an actual project perspective.

* In the U.S. the original incentive was the 10% tax credit system which was the real stimulus that created the bioenergy industry. Only recently have the traditional forest products industries become interested in being a part of the Bioenergy Association. They now see that the bioenergy industry is not competing for primary feedstocks but is interested in forest industry wastes, a complementary interest.

* In the U.S. a biofuel electric

utility can be put in for about 6¢/kWh, thus requiring 7-9¢/kWh to guarantee a viable, profitable facility. In some States where nuclear plants were dismantled, utilities are paying up to 11.5¢/kWh. This is a contrast to Canada where, for example, B.C. hydro pays 4 to 4.5¢/kWh (or only 3¢/kWh if under 5 MW) and Ontario nuclear is predicted at 3.4¢/kWh.

* Ash from these installations is more a regulatory than a technical problem. In the NE States, ash from wood burning systems is spread in the forests as fertilizer but in some areas it is classified as a hazardous waste. If urban wood wastes are utilized, care must be taken to exclude any contaminated material.

* There is U.S. activity in the co-firing of MSW and wood chips in order to optimize plant size relative to variations in the flow of MSW over the year. For example, a facility can have two boilers, one for wood and one for MSW or a system in which the fuels are mixed and the wood acts to stabilize MSW combustion. The inclusion of wood fuels may make a waste disposal project viable.

* It is expected that direct combustion will only be a niche market and the major future market for biofuel preparation and handling systems will be in large liquid fuel plants.

* It is also expected that there will be greater interaction between industry and the research community since the preparation and handling industry can support R&D in the conversion field because large biomass conversion plants would provide a market for P&H systems.

* There is a need to establish a method for sharing of information between the U.S. and Canada.

* In response to a question on potential developments in wood-based turbine cycle systems for 5-10 MW electric plants, it was noted that; a group at Princeton is attempting to obtain funding for setting up a wood gasification system to use turbines developed in the coal gasification program, TVA is involved in a study of small biofuel turbines, and SYNGAS is proposing the use of a gasifier and steam injected turbine system with anticipated costs of 3.4 to 4.5¢/kWh from waste wood

During the general discussion, comments were provided with respect to the role EMR should adopt with respect to continued encouragement of bioenergy implementation. The main points are summarized below:

* Direction for EMR should come from industry, not necessarily from the research community who may have a vested interest in doing research.

* But, industry may not be aware of their problems. For example; mills do not monitor the performance of their bark presses. They assume that the press is achieving its design specification when, in fact, performance may be lower (many mills are not getting below 60% MC from presses specified to provide 50% MC). Another example is the steam plant where, if boiler performance drops, the operators simply burn more oil to maintain output and the mill management is unaware that a combustion problem exists.

* There is a need for EMR to interact with industry. The message on bioenergy achievements must be delivered to mill management, and more particularly to mill engineering staff. This might be achieved through dialogue in conjunction with industry conferences (e.g., CPPA) or industry association meetings (e.g., CPPA Steam and Power Group).

* Industry funding (joint projects) can be a good self-selection process but business cycles have a major impact on private R&D funding. When business is good, funds are devoted to expansion of production but when business is poor, there are no funds available.

* Bioenergy optimization is very site specific. Each mill has specific problems that require on-site evaluation by a team of experts to inspect the systems and make recommendations for system improvements and optimization, i.e., and energy-audit approach.

* It is essential that government continue to support demonstrations since success of the first commercial prototype is the key to industry adoption of a new technology.

* In an era of tight money, government funding should be devoted to effective information transfer. Paper transfer is not what is required, but to encourage the community to get together for direct information exchange. For example, in the past, NRC held seminars on specific technical areas and provided financial support for experts to meet for discussions.

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